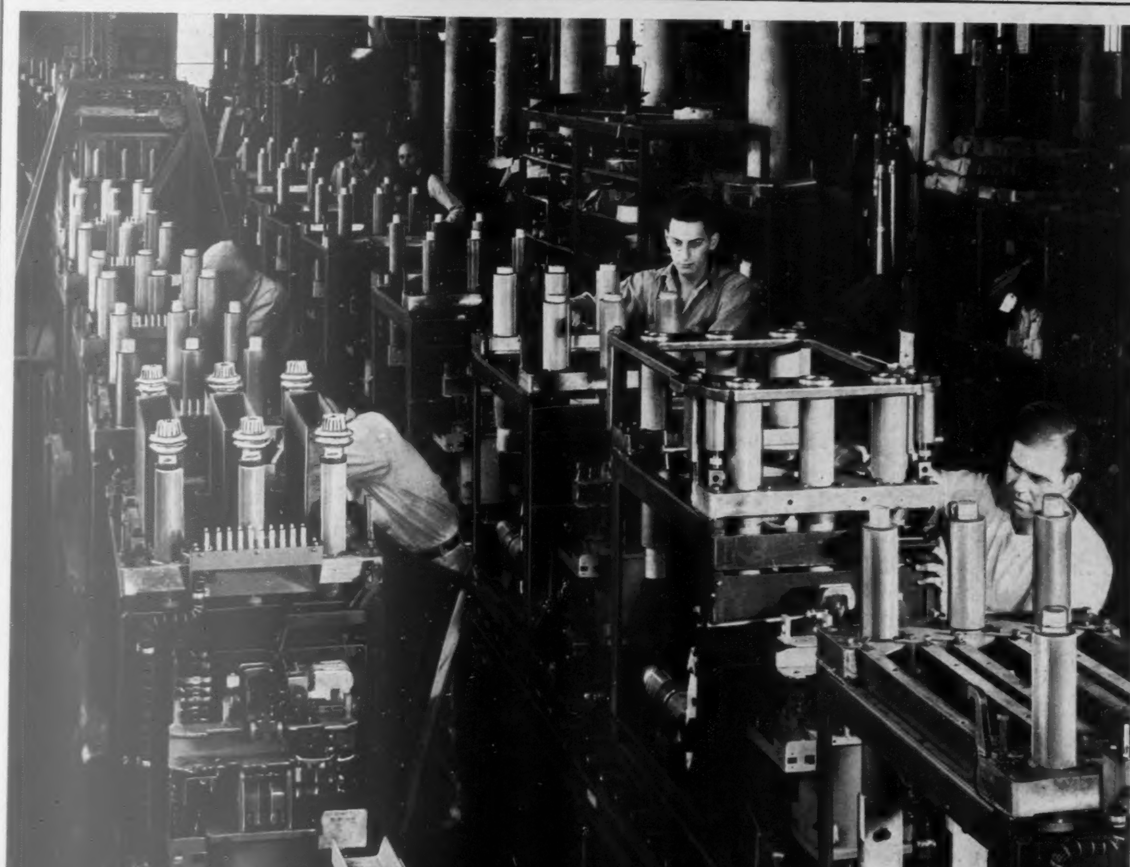
ALLIS-CHALMERS Electrical REVIEW



Third Quarter, 1949

Regulex controlled synchronous condenser at the Vandalia plant of the Illinois Power Company.

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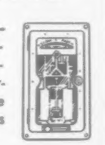

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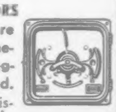

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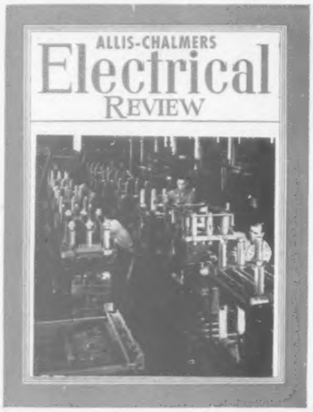

ASSEMBLY LINE production of magnetic air breakers is a long step from the one-at-a-time methods of a few years ago. After assembly and before test, each unit is aligned in a jig simulating the structure of the metal-clad switchgear which will house these safe and efficient, new vertical-lift type breakers. Air blast breaker assembly line is in the rear.

The year 1949 marks the fiftieth anniversary of the Allis-Chalmers Mfg. Company's Boston Works, where this scene was photographed. Two articles of lasting interest on the subject of circuit breakers are found in this issue on pages 4 and 26.

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Allis-Chalmers

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Contents

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HIGH-SPEED RECLOSING

H. B. ASHENDEN
Engineering Section
Allis-Chalmers Mfg. Co.
Boston, Mass.

Great progress in reducing circuit breaker reclosing time has made uninterrupted service a reality.

THE GREAT and steady growth of electric power generating, transmission, and distribution facilities has been paralleled by increasing use of electricity for industrial production. Or perhaps we should say the demands of constantly increasing production have been paralleled by the growth of electric power. It is difficult to conceive of one without the other. In any case, the expanding use of electric power to operate production machinery has created an assortment of problems as may be expected in any technological advancement. Many of these difficulties had to be solved by the combined efforts of the power companies — who generate and distribute electric power — and the manufacturers of the electrical equipment used for the purpose.

Some of the problems following the wider use of electricity in industry have been, and still are, caused by the necessity for a high degree of reliability and continuity of service. With many industries completely dependent on purchased power a brief interruption is always a great inconvenience and can also cause actual heavy monetary loss in quite a few cases. The power companies have, therefore, utilized every available means to improve service reliability and continuity, and have been active in promoting new methods. Some of the means adopted have been expensive but nevertheless used where reliability was important. Multiple transmission lines, for example, are quite expensive but obviously improve reliability since trouble is unlikely to involve more than one line at a time.

One of the less expensive but effective means for improving continuity has proved to be faster interruption of faults rather than attempting to eliminate them entirely. This has created a demand for much faster circuit breakers. Not long ago, a breaker which would interrupt a fault in eight cycles was considered fast. At present, standard high voltage breakers are expected to interrupt in five cycles, and even three cycles in some cases. In addition, circuit breakers capable of high-speed reclosing were found to be one of the more economical tools for improving service continuity and the demand for such breakers became insistent. Producing standard breakers at reasonable cost to meet the demand posed something of a problem for the manufacturer of such equipment as the speed increase considered desirable was rapidly revised upward until it became relatively large. Some of the methods and experiences used to solve that problem are both interesting and informative.

Reclosing practice changed with time

First, perhaps, we had better consider briefly what is meant by high-speed reclosing of a breaker and why that performance characteristic is in demand. The practice now known as high-speed reclosing is regarded as relatively new, but is, of course, merely a faster version of the automatic reclosing of power circuit breakers which has been in use for 30 years and more. However, quite different results are possible with the greatly increased speed. In the earlier years, operating speed was not a factor as some intentional time delay between opening and reclosing was customary. Later, reclosing after the first trip-out without intentional time delay began to be practised. There resulted a reclosing time interval of the order of one second in the relatively slow breakers of the day. Nevertheless on many feeders the deenergized time was short enough to prevent dropping most of the load and improvement of service was, therefore, substantial. However, it seemed evident a shorter deenergized time should permit holding more types of load through an interruption due to a temporary fault. In fact, if the time interval was short enough, the user would not even be aware there had been an interruption and service continuity would be preserved. Considerations such as these prompted the demand for increasingly faster operating speeds in all ratings but principally for breakers used on feeders.

Very soon still faster speeds were required of high voltage breakers used on transmission lines. Here the requirement was to open a breaker to clear a temporary fault and reclose it quickly enough to preserve synchronism between two generating sources. The economic advantage was obvious, as a single circuit tie line could then be made almost as reliable as a double circuit tie if temporary faults could be cleared without disturbing continuity of power flow. For preserving synchronism the shorter the reclosing interval the better, but the deenergized time must be enough to permit arc to deionize.

Eventually a time interval of about twenty cycles between energizing trip coil and reclosing of contacts, or a deenergized time of approximately 15 cycles, was considered to be about the best compromise between shorter intervals required by stability characteristics in some cases and the minimum deenergized time necessary to make the probability of an arc restrike small. This time interval has now been written into the standards for high voltage breakers. High-speed reclosing has therefore come to mean reclosing in twenty cycles for the present, at least. It may change in the future. The performance required of circuit breakers usually does.

Reclosing poses dynamics problem

Pausing to consider what precisely occurs when a large breaker recloses may result in better appreciation of the problem posed by such a speed requirement. On a large high voltage breaker the movable members which support the contacts weigh many pounds. These must be moved down a couple of feet, be re-

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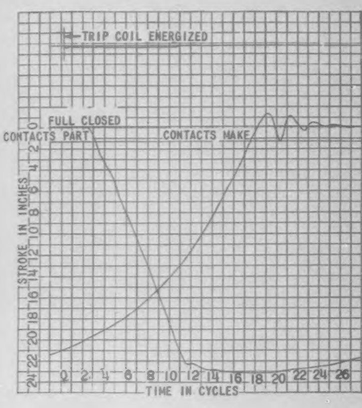
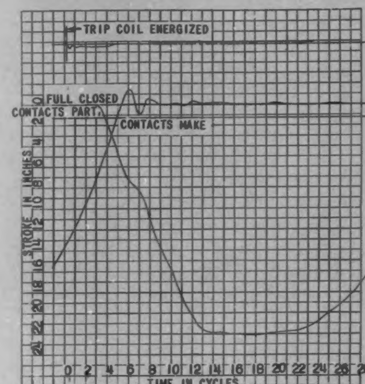
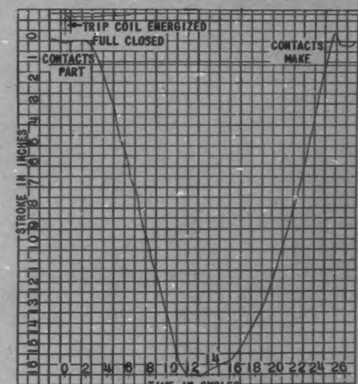


SPEEDGRAPH of a typical 1938 solenoid-operated 115-kv breaker shows a reclosing time of about 50 cycles. **(FIGURE 1)**



RECLOSING SPEED was raised to 32 cycles by reducing mass of operator. Solenoid current was 340 amp. **(FIGURE 2)**



BY 1939 several 69-kv breakers achieved a reclosing speed of 25 cycles, using oversize operator mechanism. **(FIGURE 3)**

versed, and moved back the same distance, all in less than a third of a second. The speed is almost faster than the eye, and the force required to accelerate the mass of these parts is considerable. In addition, the time interval must include energizing the trip coil to lift its plunger and release the latch. There is also the mass of rods, cranks, and links of the necessary mechanism to move. The travel is not as great in these parts, but the force required is far from negligible. In one case it was calculated that the force required to accelerate the connecting rod between poles during the first inch or two of opening stroke was greater than that for the contact members.

As will be indicated later, the fundamental problem of meeting this speed requirement was pretty well solved in a few years after the demand was evident. The war years then delayed development but, nevertheless, within a ten-year period the reclosing speed of standard high voltage breakers in regular production was at least tripled. In looking back it seems no small feat for all of the manufacturers of this type of equipment.

Development policy

By the late 1930's there was no question about the trend. Experiments and study to find the best method to increase speed of breakers were begun in earnest. There was much discussion as to the best means and various proposals. One method to obtain quick reclosure appeared to be to open contacts only partially. However, there was then, and there still is, considerable difference of opinion as to the necessity for a full opening stroke on reclosing. Those responsible for circuit breaker design in this case believed that the safety of the time-tried mechanically trip-free mechanism and the dielectric strength inherent in a full opening stroke should not be sacrificed. They won the argument and both of these were retained in spite of the problems imposed.

Speedgraphs show progress

Once a few fundamentals were decided on, experiment and development proceeded and progress was fairly rapid at first. Perhaps the simplest way to follow and discuss this development over the early years is by use of typical speedgraphs taken at intervals. Speedgraphs are records of tests made with a graphic speed analyzer used in analyzing the performance of experimental breakers or for routine tests on standard breakers. The analyzer consists essentially of a drum revolved at a known speed by a synchronous motor and a stylus temporarily attached to the breaker lift rod and arranged to move vertically over the drum with motion of the lift rod and contacts. The stylus draws a graph on a chart wrapped around the drum. The resulting speedgraph therefore shows time in cycles as the horizontal axis and breaker stroke on the vertical axis. A magnetically-operated stylus may be connected in the trip coil or other circuit to indicate the timing of an accessory relative to breaker motion.

By 1938 there had been some increase in speed of breakers but reclosing time of large high voltage breakers was still around one second. Figure 1 is a speedgraph of a typical standard breaker produced at that time. It shows reclosing time of 50 cycles. Note the long time of about twelve cycles that the breaker remains full open and the rather slow acceleration after the solenoid begins to move. This characteristic was

very typical of solenoid-operated breakers at that time. The steady state closing current of this solenoid was about 190 amps at 125 volts.

Challenge of first reclosing standard

The first objective in the development of faster breakers was to meet the requirement of 35-cycle reclosing speed established by NEMA Standards in 1938. The obvious solution to the problem proved to be sufficient. Moving parts were redesigned to decrease mass where possible and increase strength where necessary to withstand greater forces required to gain speed. The power of the solenoid was increased. The mechanical trip-free system was improved to obtain faster relatching, or recoupling, between the operator and breaker mechanism during the opening stroke. The result is indicated by Figure 2 which shows a reclosing time just under the 35 cycles required. Note that the breaker stayed full open a much shorter time than in Figure 1 and that acceleration is much faster. The solenoid delivered much more power but required a larger battery. The closing current was about 340 amps at 250 volts or the power demand was about 3½ times that required for the slower breakers of the same 115 kv rating.

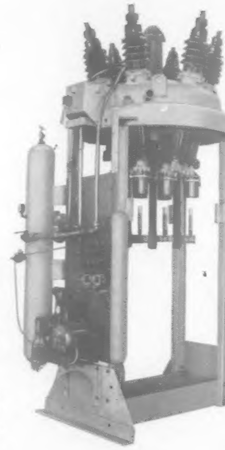
Results of tests such as that shown in Figure 2 on a number of breakers of various ratings indicated that the solenoid operator might not be adequate for the even higher speeds which the users desired. It was doubtful whether mass could be reduced substantially and, obviously, much more force would be required to produce the necessary acceleration. For a solenoid, this undoubtedly meant a high closing current and a more expensive battery. Also, the inherent time delay in build-up of flux and resulting force in a large solenoid was an obstacle to higher speed. Experimental work on other types of operators already under way was speeded up in an attempt to find a better one for the purpose. Various combinations such as motor operators, motor-driven cam operators, cocked springs, and others were tried.

Twenty-five-cycle reclosing in 1939

At a time when this experimental work had yet to provide any conclusive results, it became necessary to manufacture some 69-kv breakers capable of reclosing in 25 cycles. The best means to provide such speed was in doubt, but it was decided to try a very powerful solenoid. The large operator used for high voltage breakers was applied to the lighter 69-kv breaker. After some trial and experiment followed by changes, a combination was produced with characteristics shown in Figure 3. This speedgraph, made in the summer of 1939, indicates that contacts are at rest at the bottom of the stroke a very short time and acceleration during closing is fast. The reclosing time was 24½ cycles. Other tests showed progress in time of recoupling or latching of breaker to operator, as it occurred about five cycles after the trip coil was energized. This appeared very fast compared to previous breakers but was still too slow if higher speeds were to be attained with a mechanically trip-free breaker. For such a breaker the closing means should not be energized until recoupling occurs, as otherwise the operation may be trip free and the breaker fail to close at all.

While the speed required was attained in this case the closing current found necessary provided still more evidence that the solenoid operator was not practical for high speed operation. The coil finally used had a resistance of 0.115 ohms

PNEUMATIC OPERATION of oil circuit breakers had been tried on a small scale about 1899. This unit was in regular service until about 1940. **(FIGURE 4)**

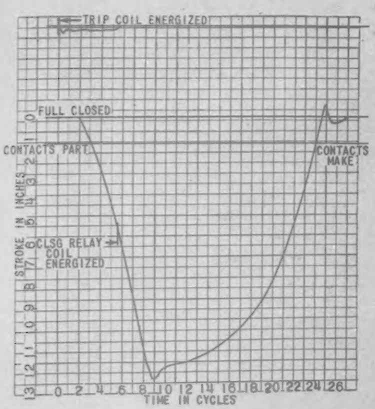


EXPERIMENTAL OPERATOR using compressed air speeded reclosing but slow release of air under piston kept reclosing time above 18 cycles. **(FIGURE 5)**

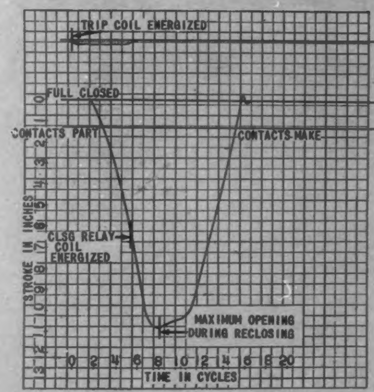
which corresponds to a steady state closing current of about 1,000 amps at 125 volts. During the very short closing time the current would not build up to this value, but the large battery capacity, available in this special case, would always be necessary and even more capacity would probably be required for a larger breaker. Such a solution did not seem reasonable or practical for standard breakers.

Unique experimental breaker

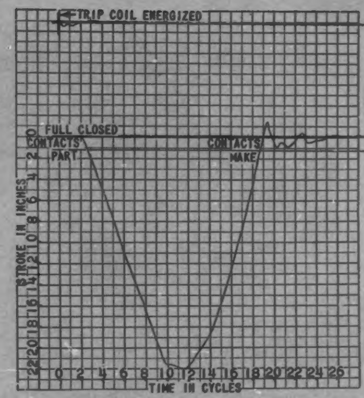
Among the operators under experimental consideration was one actuated by compressed air. Air operation of oil circuit breakers is far from new as it was in use about the turn of the century and at least one of these old pneumatically-operated breakers installed about 1899 is known to have been in service until around 1940 (see Figure 4). However, solenoid, motor, and spring operators had been standard practice for so long that the idea seemed an innovation to the present generation of designers. Compressed air as a source of energy for fast operation has an obvious advantage as, once it is released under a piston, force to produce action is immediately available without the inherent time delay existing in the solenoid. Moreover it was successfully producing fast operation in the air blast breakers also under development at the time. A trial seemed worthwhile and an experimental breaker was built which was quite unconventional as it was both opened and closed pneumatically, was an outdoor three-pole-in-one tank, 23-kv breaker, and was not mechanically trip free. The operating cylinder was placed on the vertical axis of the breaker outside of and on top of the insulator support. Figure 5 shows the arrangement. As finally tested it would open in seven cycles and close in seven cycles, but the best reclosing time obtainable was 18 cycles. Failure in obtaining 14-cycle reclosing was due to difficulty with air dumping, that is, quick removal of air from under the piston after closing. Incidentally, this difficulty seemed one more good reason to retain the mechanical trip-free feature. The experiment served its purpose by proving conclusively that reclosing times of the order of 15 to 20 cycles could be attained on a modern oil circuit breaker by pneumatic operation. It also showed that pneumatic opening of the breaker did not increase speed materially and it was decided that a combination of the con-



CONCLUSIVE EVIDENCE of speed and advantages of pneumatic operation was made on solenoid type 46-kv breakers. **(FIG. 6)**



PNEUMATIC RECLOSER on same breaker as that in Figure 6 upped reclosing speed from 24 to 15½ cycles. **(FIGURE 7)**



RECLOSING TIME under 20 cycles on 115-kv breakers was accomplished in 1941. Note steep closing curve, long stroke. **(FIG. 8)**

ventional magnetic tripping with spring acceleration plus pneumatic closing would provide much faster reclosing times than previously obtained and probably as fast as was likely to be necessary.

Pneumatic operation preferred

However, before a decision was made to depend entirely on the pneumatic operator for the high speed reclosing development, another experiment was performed. A standard 46-kv breaker with modern solenoid operator was assembled and tested. A pneumatic cylinder was then substituted for the solenoid and another test run without any change in adjustments. The results are shown in Figures 6 and 7. Figure 6 is a speedgraph of solenoid operation with a reclosing time of 24 cycles. Note the contacts stayed open about 8 cycles before the solenoid attained sufficient force to start closing. For pneumatic operation Figure 7 shows a reclosing time of 15½ cycles. In comparing the two curves it is obvious the improvement is due to less delay at the start of the closing stroke by the pneumatic operator. Closing speeds as the breaker approaches closed position are about the same for both as indicated by the slope of the curves. This experiment did not leave much room for doubt as to which operator was preferable for speed.

Twenty-cycle reclosing in 1940

Strangely enough, the first modern breaker shipped with pneumatic operator was not required to reclose rapidly, although this operator had been developed solely to obtain high speed operation. However, the economic advantage of pneumatic operation where large batteries were not available was obvious as it would not be necessary to buy and maintain such batteries. Consequently, about 1940 when a large eastern utility wished to install some 69-kv breakers in an isolated location where there was no battery, pneumatic operation was suggested. In this case, the standard solenoid operator was converted to pneumatic operation by simply replacing the solenoid with a piston and cylinder. The mechanically trip-free mechanism was not altered. Although reclosing speed was not important, a test was made. The reclosing time was found to be about 20 cycles although the breakers were the same design which were reclosed in 25 cycles with difficulty when a solenoid was used for operation. This early 1940 installation has given excellent service and also provided field experience. Figure 10 shows one of these breakers. Note the air compressor at the top of the operating cabinet and the air receiver at the side which was the arrangement in early designs.

The first pneumaticallly-operated 115-kv breakers, capable of reclosing in 20 cycles, were installed in 1941. Figure 8 is a speedgraph for one of these breakers. Reclosing time was under 20 cycles. Contacts went full open but were very quickly reversed by pneumatic operator and closed at high speed as indicated by the steep slope of closing part of the curve. Recoupling time is not shown, but had been reduced to some four cycles which aided materially in attaining fast reclosing indicated.

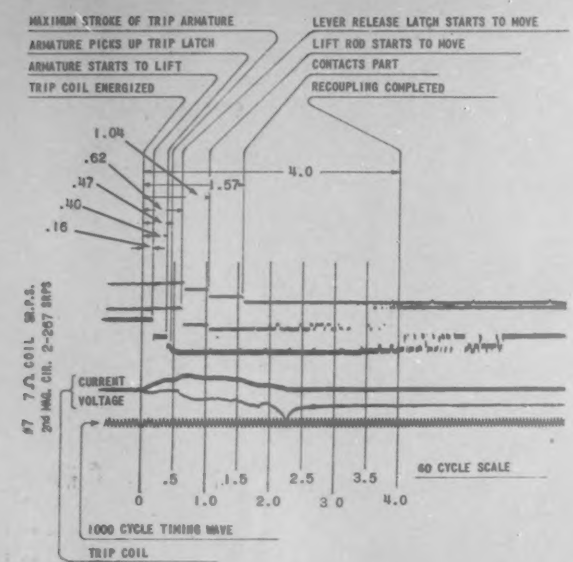
Integrated design attains goal

As the foregoing indicates, the fundamental problems in making large breakers capable of high speed reclosing had been pretty well solved by 1941, or about three years after development actually started. Nevertheless, there was still much to be done before standard commercially-produced apparatus capable of required speed could be made available. The breakers produced in the early 1940's have performed well, but must be considered custom-built equipment and not standard production items. Obtaining the desired functioning of these breakers frequently required much special work, and sometimes changes after assembly. Many refinements were desirable and necessary before these devices were ready for standard production.

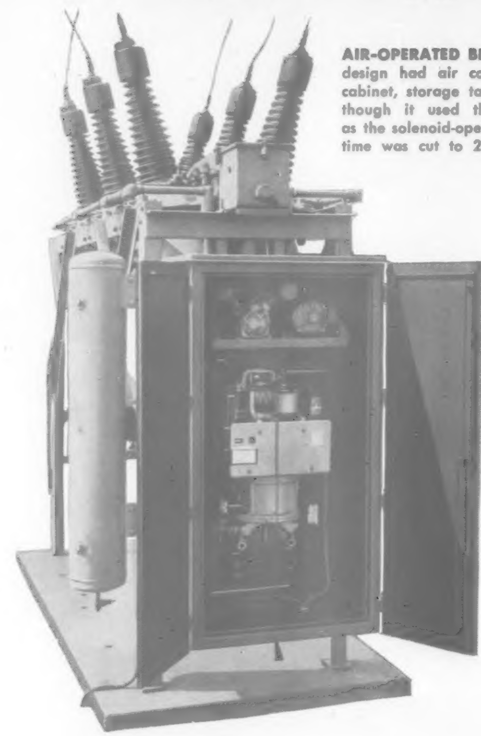
This development was delayed during the war years, but finally was undertaken. There is no need here to discuss all the details which needed attention in complete redesign of standard breakers for five-cycle interruption, as well as 20-cycle reclosing, but some mention of the air system, mechanical trip-free system, and the control arrangement may prove interesting.

Air system utilizes nature's laws

The design of a unit air system for production in quantity at reasonable cost required much thought and time. As air com-



TEST OSCILLOGRAM indicates some of the problems involved in the mechanics of high-speed reclosing. Total time above is about six cycles. (FIG. 9)



AIR-OPERATED BREAKER of the 1940 design had air compressor at top of cabinet, storage tank on the side. Although it used the same mechanism as the solenoid-operated units, reclosing time was cut to 20 cycles. (FIG. 10)

pression and storage were new in circuit breaker operation, there was no accumulated experience on which to base a design, and it was necessary to obtain information from other fields. Railroad practice appeared to be as useful a guide as any because of the necessity for reliability in both fields, and much data was obtained from that source. Reliability, simplicity, and ruggedness were stressed at all times in this design. Among the problems was the elimination of any probability of failure due to freezing. Piping was carefully arranged to avoid pockets, for example. The possibility of condensation of moisture, always present in air, to water at the point of use, followed by freezing, also had to be considered.

Fortunately, the condensation of water to moisture at the point of use can be avoided by the simple expedient of maintaining that point at a higher temperature than the air storage reservoir. The air reservoir or tank is therefore mounted outside the operating cabinet. The latter is maintained at a higher temperature than the outside air and the tank by a continuously energized heater, reinforced by a thermostat-controlled heater in cold weather. It is not necessary to maintain the operating cabinet above 32 degrees F to prevent trouble due to freezing at the point of use, but merely above the temperature at the tank. There is, however, some water in the bottom of the air receiver or tank left there by the warm air from the compressor as it cools in storage. To prevent freezing of this water a small amount of anti-freeze is added at the beginning of cold weather.

Perhaps the best evidence that the solution to the freezing problem works is that some very similar systems of early design have gone through several severe New England winters with no trouble. In Figure 13, a standard unit air system may be seen mounted in place at the bottom of the operating cabinet. It consists essentially of a tank which is beneath the cabinet, mounting plate on the tank which forms the bottom of the cabinet, motor, compressor (behind the motor), and the piping. This figure also shows the pneumatic operator in the middle of the cabinet. Figure 14 is a side view of the same cabinet with the compressor visible at the lower left and with a side view of the operator above.

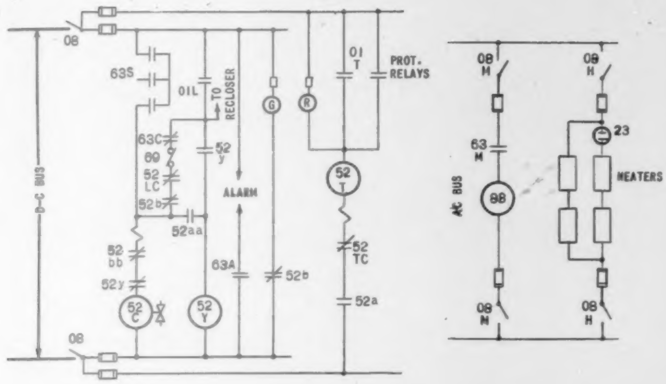
Mechanically trip-free feature retained

For a mechanically trip-free breaker the whole trip system with its compound latching mechanism is a very important part of the operator. It must be very reliable, and for high-speed operation it must also trip and recouple very fast. The system developed for the earlier high-speed breakers was reliable and satisfactory in many respects, but was not considered fast enough for the final design. It was desired to have a mechanism recouple after tripping as early in the opening stroke as possible, preferably within three cycles of the time the trip coil was energized. The solution of the problem proved to be quite a task.

Among other methods a magnetic oscillograph was used to help analyze the motion of the various parts. Figure 9 is typical of the oscillograms obtained from this series of tests and is presented here principally to indicate the very short time intervals involved. The full length of the oscillogram represents a time interval of about 0.1 second. Obviously, the motion of some of the component parts takes place in an extremely short time. Note that recoupling time shown is about four cycles as there was still much work ahead at the time this particular oscillogram was taken. It does not represent tests of the final design, but was selected for its readability. After more trials and changes the desired improvement was substantially obtained.

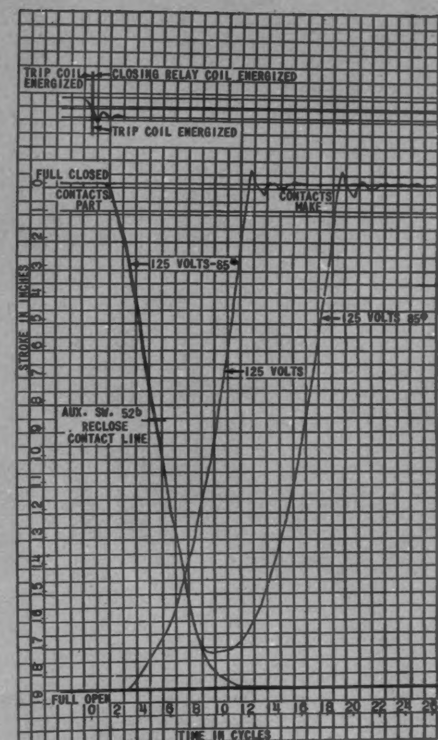
Control scheme improved

The control scheme for the early design was essentially the same as the time-tried two-relay scheme used for the solenoid operator. The only difference was a substitution of a solenoid valve for the main closing solenoid, and addition of the neces-



SCHEMATIC DIAGRAM of pneumatic operator. **(FIGURE 11)**

01C — Closing contact of control switch.
01T — Trip contact of control switch.
08 — Control power switch.
08H — Heater power switch.
08M — Compressor motor switch.
34 — Thermostat.
52a — Breaker auxiliary switch—closed when breaker is closed.
52aa — Operator auxiliary switch—adjusted to close as operator reaches closed position.
52b — Breaker auxiliary switch—open when breaker closed.
52bb — Operator auxiliary switch—with blow-out—adjusted to open at the end of closing stroke.
52c — Solenoid valve—opens when energized to admit air under piston and close breaker.
52LC — Latch check switch—prevents energizing closing circuit until breaker and operator are recoupled.
52Y — Auxiliary control or anti-pump relay.
63A — Pressure switch—closes contact as pressure drops to approach setting of 63 C.
63C — Pressure switch—opens contact as pressure reaches minimum safe closing value.
63M — Pressure switch—acts as pressure regulator.
63S — Pressure operated contact—closes to seal-in closing circuit when air is under closing piston.
69 — Switch—opens when breaker tripped from manual trip rod—manual reset.
88 — Compressor motor.
G — Green light.
R — Red light.



TODAY'S STANDARD BREAKERS provide 20-cycle or better (18 cycles shown above) reclosing time and five-cycle interrupting. Note how the closing relay coil is energized early in the cycle. **(FIGURE 12)**

sary pressure switches. It was the natural solution at the time, as the scheme was known to be reliable, and to function well. Moreover, the pneumatic operators were much the same as the solenoid operators with air cylinder in place of the solenoid.

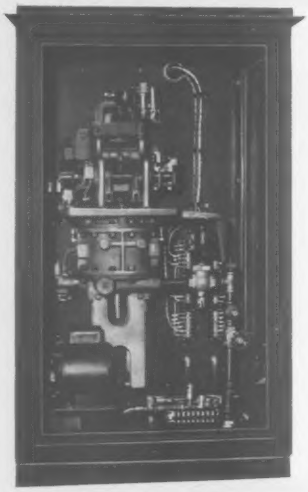
After some experience it became obvious that the arrangement was not entirely satisfactory for obtaining the highest possible speed with minimum air consumption. The principal difficulties may be summarized as follows:

1. Operating time of X relay, although under two cycles, becomes a very considerable delay at such speeds as 20-cycle reclosing.
2. Air consumption was higher than necessary due to delay in deenergizing the solenoid valve caused by operating time of Y relay plus dropout time of X relay.
3. Occasionally someone would forget to open the safety shut-off valve after maintenance work. If an attempt was then made to close electrically, the X relay would seal in the closing circuit and, since the breaker could not close, the solenoid valve coil usually burned out before the error was noted.
4. The trip circuit did not clear fast enough to avoid delay in reset of trip plunger which interfered with fast recoupling.

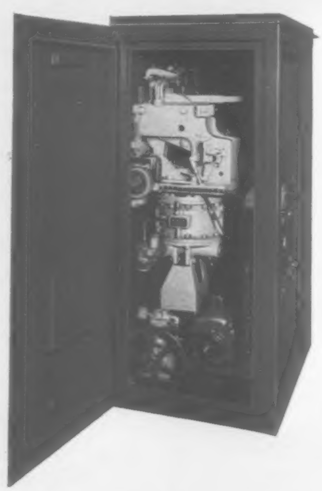
After some consideration of faster closing relays it was decided to eliminate the relay altogether. As the solenoid valve operating current was well within the "make" rating of the usual control switch, the relay seemed unnecessary if other means could be found to perform its other functions of sealing in the closing circuit and breaking the closing current after operation was completed. A pressure switch was added to perform the seal-in function, and difficulty No. 3 above was thereby eliminated since the circuit could not seal in unless the safety shut-off valve was open. A mechanically operated switch with blow-out was added to cut off the air at the proper point in the closing stroke, and thus solved No. 2 above. This switch is 52bb in Figure 11. To eliminate trouble due to No. 4 a contact, 52TC, was connected in series with the trip coil. This is provided with a blowout and opens as soon as the trip coil plunger lifts. The resulting arrangement is shown schematically in Figure 11.

Conclusion

These then are some of the highlights in the development of standard circuit breakers to include one particular characteristic, high-speed reclosing. It is perhaps typical of many of today's developments requiring the work of many individuals and organizations from the inception of the idea through ex-



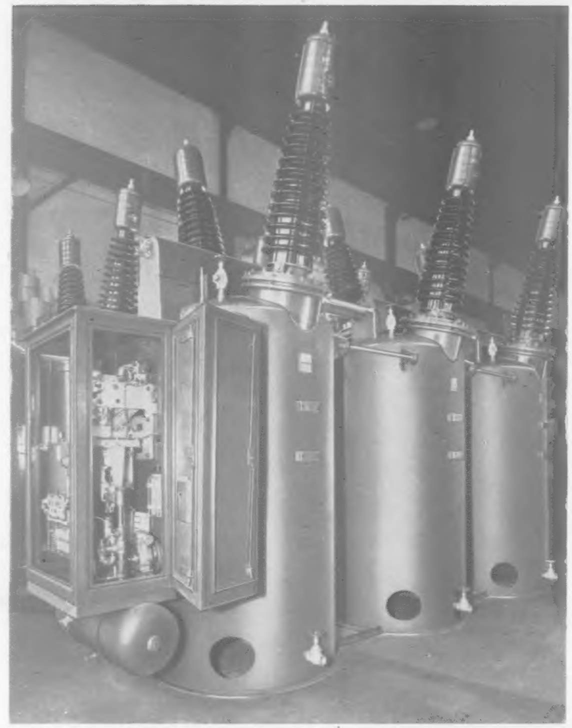
MODERN AIR SYSTEM is shown in the front view of the operator cabinet. Note simple, direct piping from tank to cylinder. Solenoid closing valve is in air line and dump valve at left of cylinder. **(FIGURE 13)**



SIDE VIEW of cabinet shown in Figure 13 reveals the sturdy construction used to withstand shock of high-speed operation. In cold weather heater strips keep cabinet warmer than the air tank. **(FIGURE 14)**

periments, trial, and field experience, to the inclusion in a standard commercially-produced product.

The development can perhaps best be evaluated in terms of the end result, the features and characteristics of the present standard breaker. Figure 15 shows a production floor view of one of the complete standard breakers now in regular production. Figure 12 shows the characteristics of one of these present-day breakers. Opening, closing, and reclosing curves are shown on the same speedgraph. Contact part time is less than tyo cycles since this is a standard five-cycle breaker. The closing time is about 11 cycles. Reclosing time is slightly over 18 cycles.



AIR-OPERATED BREAKERS on production test floor exemplify the results of the many years of development reviewed. Speed graph in Figure 12 typifies performance of these 161-kv, 1,500,000-kva units. **(FIGURE 15)**

The design has been integrated throughout for high-speed pneumatic reclosing. The retention of all of the advantages of the full mechanically trip-free feature have been made possible by the development of an ultra high-speed recoupling mechanism which permits applying closing power during the opening stroke. The margin of safety of substantially the full opening stroke is, however, retained even on 20-cycle reclosing operations.

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GUIDE CASE VIEW of shop-assembled, fixed propeller hydraulic turbine shows that modern design is not limited to futuristic homes, store fronts or stage settings, but has a place in the construction of heavy industrial equipment. Speed ring barely visible in the foreground, the eight feet high guide vanes and the head cover seen through them are all of welded plate steel construction. Project is part of three concrete spiral casing turbines, each rated 6,975 hp under 21-foot head at 80 rpm, being built for the U. S. government's Sault Ste. Marie hydro-electric station.

Variations...

IN THE DIELECTRIC STRENGTH OF AIR

Moisture content and air pressure between electrodes affect voltage at which sparkover will occur.

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MANY TYPES of electrical apparatus depend upon air as a dielectric. The electrical strength of air depends upon the distance between parts, shape of the electrode, electrode material, voltage frequency, its polarity, and atmospheric conditions.

Correction factors which permit reference to an arbitrarily established "standard atmosphere" have been published but these are scattered through a number of Standards.[1] The procedure is shown for the establishment of standard sparkover levels when the tested sparkover level and the atmospheric conditions at the time of test are known. Conversely, the expected test sparkover level can be arrived at when the standard sparkover level and the existing atmospherics are known. During the dielectric tests on many types of electrical apparatus, gaps of one form or another are used for voltage measurement. There are several ways in which atmospherics effect the setting of these gaps in order that specified withstand voltage levels be applied.

The sparkover level of most insulators is influenced by both the barometric pressure and the moisture content of the air. Gaps on the other hand, as used to limit voltage on a system and to measure voltage in laboratory tests, depend on the barometric pressure and may or may not be influenced by the humidity of the atmosphere, depending upon the type of gap. A sphere gap is only affected by the barometric pressure, whereas a rod gap is influenced by both the barometric pressure and humidity.

Obviously, atmospheric conditions are a variable and depend upon the barometric pressure and the humidity. The influence of barometric pressure is manifest by a changing air density. The most convenient measure of humidity, the moisture content of the atmosphere, is vapor pressure.

"Standard Atmosphere" for all dielectric measurements is:

Barometer 29.92 inches (760 mm)
Temperature 77 degrees F (25 C)
Vapor Pressure 0.6085" (15.45 mm) of Mercury

[1] See bibliography

Relative air density

Sparkover voltage for a given gap or insulator decreases with decreasing barometric pressure and with increasing temperature. The relationship of these factors is contained in the expression for relative air density (RAD):

$$\mathrm{RAD} = \frac{17.93\ P_b}{459 + t} \qquad \text{Eq. 1a}$$

where

P_b = barometric pressure, inches of mercury
t = temperature, degrees F

The equivalent expression in metric units is:

$$\mathrm{RAD} = \frac{0.392\ P_b}{273 + t} \qquad \text{Eq. 1b}$$

where

P_b = barometric pressure, mm of mercury
t = temperature, degrees C

A graph for the ready determination of relative air density is shown in Figure 1.

Vapor pressure measurement simplified

The sparkover voltage for a given gap or insulator decreases with decreasing vapor pressure. A wet and dry bulb thermometer is used to measure humidity. During the process, air must be circulated past the thermometers at a velocity of 9.84 feet (3 meters) per second, or a sling psychrometer must be used. Temperature measurements can be reduced to vapor pressure with the assistance of the Smithsonian Meteorological Tables or by the following formula:

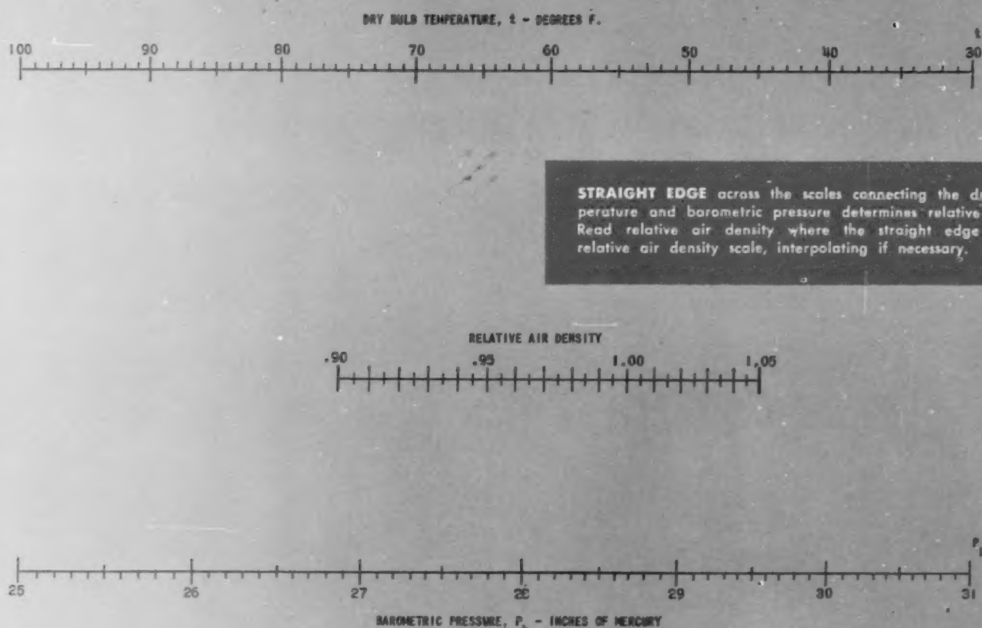
$$VP = VP_s - 0.000367\ P_b\ (t-t')\left(1 + \frac{t'-32}{1571}\right) \qquad \text{Eq. 2a}$$

where

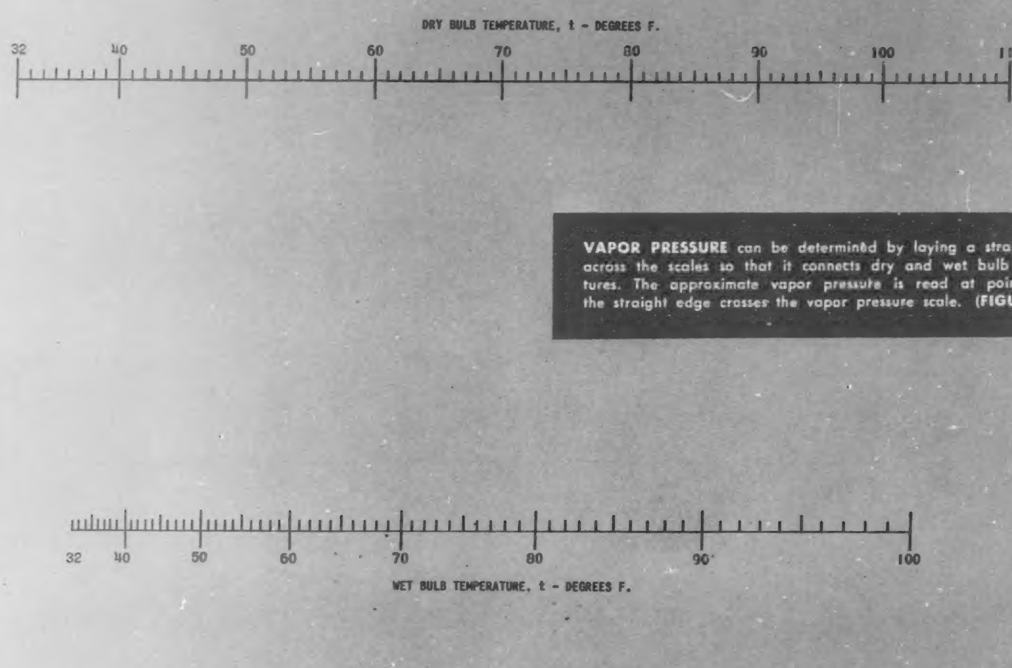
VP = vapor pressure, inches
VP_s = pressure of saturated aqueous vapor at the wet bulb temperature, t', inches
t = dry bulb temperature, degrees F
t' = wet bulb temperature, degrees F
P_b = barometric pressure, inches of mercury

The equation in metric units is:

$$VP = VP_s - 0.00066\ P_b\ (t-t')\ (1 + 0.00115t') \qquad \text{Eq. 2b}$$



STRAIGHT EDGE across the scales connecting the dry bulb temperature and barometric pressure determines relative air density. Read relative air density where the straight edge crosses the relative air density scale, interpolating if necessary. **(FIGURE 1)**



VAPOR PRESSURE can be determined by laying a straight-edge across the scales so that it connects dry and wet bulb temperatures. The approximate vapor pressure is read at points where the straight edge crosses the vapor pressure scale. **(FIGURE 2a)***

** See footnote on page 15*

where

$VP =$ vapor pressure, mm

$VP_s =$ pressure of saturated aqueous vapor at the wet bulb temperature, t', mm

$t =$ dry bulb temperature, degrees C

$t' =$ wet bulb temperature, degrees C

$P_b =$ barometric pressure, mm of mercury

The vapor pressure expression is rather complex to set up in chart form. In Figure 2 it has been broken into three parts, the sum of which gives the desired quantity. The lead chart Figure 2a has been made for a barometric pressure of 29 inches and a constant wet bulb temperature of 60 degrees F. These values were chosen because they represent average annual conditions for Milwaukee. Figure 2b shows the correction for the departure of barometric pressure from 29 inches. The correction for the departure of the wet bulb from 60 degrees F is shown in Figure 2c. It is imperative to observe the sign of the correction factors. The wet bulb correction is nearly negligible. Experience will indicate whether the correction is justified in every instance.

Many atmospheric corrections used

Quite a number of humidity correction curves are in existence. These corrections depend upon the type of apparatus, whether it is 60 cycle or impulse voltage. If it is impulse voltage, the polarity of the wave is important. Various humidity correction curves current in American Standards have been accumulated in Figure 4.

For best results the vapor pressure at the time of test should be between 0.3 and 0.6 inches (7.6 and 15.2mm respectively).

The equation which relates the voltages and the atmospheric correction factors is:

$$V_s = V_t \frac{H}{D} \qquad \text{Eq. 3}$$

where

$V_s =$ standard voltage under standard atmospheric conditions

$V_t =$ test voltage under prevailing atmospheric conditions

$H =$ humidity correction factor

$D =$ relative air density

Correction factors are applied only to sparkover voltages for which the disruptive discharge occurs in air. Where the disruptive discharge occurs as the breakdown of solid or liquid dielectric, no atmospheric correction is applied.

Correcting sphere gaps

Sphere gap sparkover voltages are subject only to correction for relative air density. Humidity has negligible effect unless condensation takes place on the sphere surfaces. A small humidity effect has been observed using 12.5 centimeter spheres, but this lies within the tolerance of the standards. In Equation 3, H is equal to unity.

For a given gap, the sparkover voltage decreases with decreasing barometric pressure and increasing temperature. This variation may be considerable at high altitudes. When the variation from sea level is not great, the relative air density may be used as the correction factor; when it is great, or greater accuracy is desired, a correction factor from the curves in Figure 3 should be applied to the relative air density.

Density, humidity affect rod gaps

A rod gap consists of two half-inch square rods, square cut on the ends and coaxially mounted. The sparkover of such a gap is affected by both humidity and relative air density. The humidity correction factors for this type gap are given in Figure 4.

The full humidity correction is applied to the critical sparkover value and is graded with respect to time when the time to sparkover is less than that to critical sparkover. When the time to critical sparkover is 10 microseconds or more, the correction is reduced in the direct ratio the time to sparkover bears to 10 microseconds. When the time to critical sparkover is less than 10 microseconds, the correction is reduced in the direct ratio that time to sparkover bears to time to critical sparkover.

The sparkover voltage of the several types of insulators and of apparatus is affected by humidity and relative air density in a manner similar to rod gaps. The same rules apply for the correction at critical sparkover and for volt-time curves. Correction factors available for insulators and apparatus are given in Figure 4.

Full magnitude humidity correction factors are applied only to voltages above 141-kv crest (100 kv rms). When the voltage is below 141-kv crest, the correction is decreased in proportion to voltage, thus:

$$H' = \frac{V}{141}(H\text{-}1) + 1 \qquad \text{Eq. 4}$$

$H' =$ adjusted humidity correction factor

$H =$ full humidity correction factor from apparatus curves

$V =$ test voltage, crest

With the assistance of available atmospheric correction factors, it is possible to duplicate test results on a given specimen in any one laboratory to well within ± 5 percent from the probable true average dry flashover, and to within ± 8 percent on a given specimen when tested in different laboratories.

The relative air density equation provides a means for determining the sparkover of electrical apparatus at high altitudes.

Examples:

1. *To find relative air density*

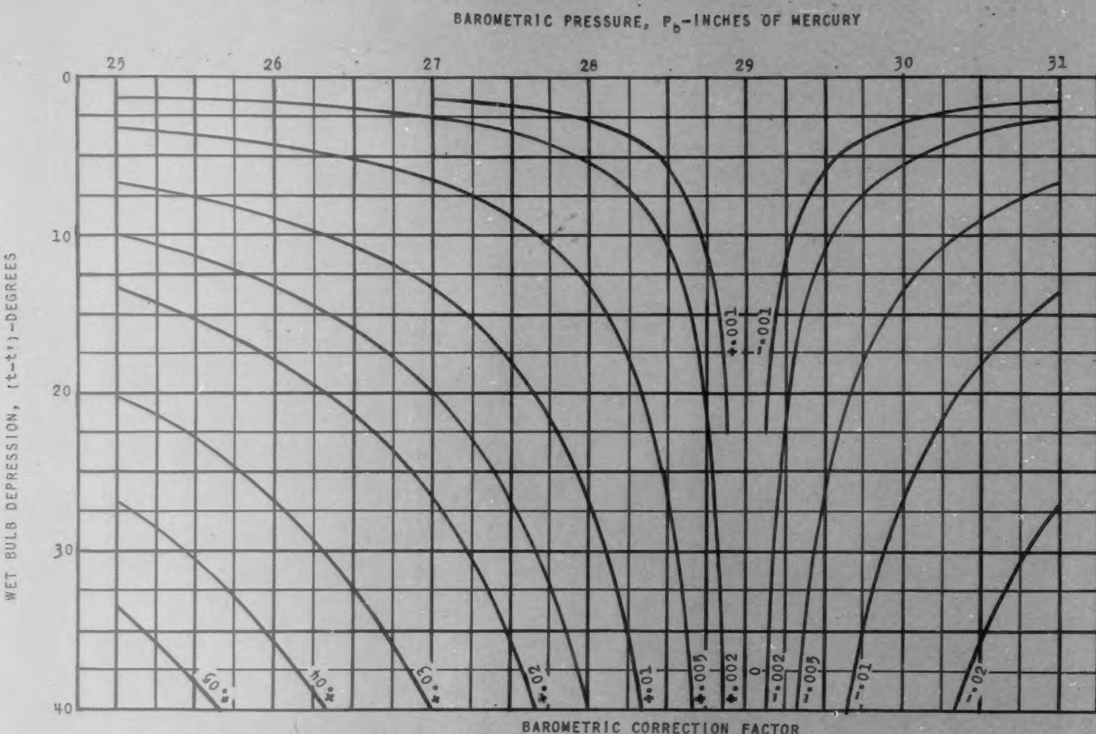
Given: Barometer = 28.95 inches, air temperature = 72 degrees F.

Use: Figure 1. At intersection of 28.95 inches and 72 degrees F, read Relative Air Density = 0.975.

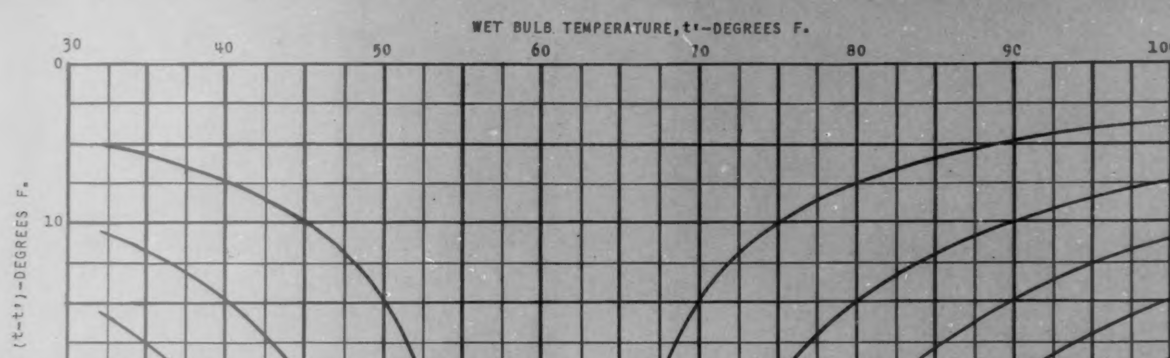
2. *To find vapor pressure*

Given: Dry bulb temperature = 62 degrees F, wet bulb temperature = 46 degrees F, barometer = 27.50 inches.

Use: Figure 2a. Connect the dry and wet bulb temperatures with a straight edge and read the vapor pressure (at chart conditions) where the straight edge cuts the vapor pressure scale as 0.137 inches of mercury.

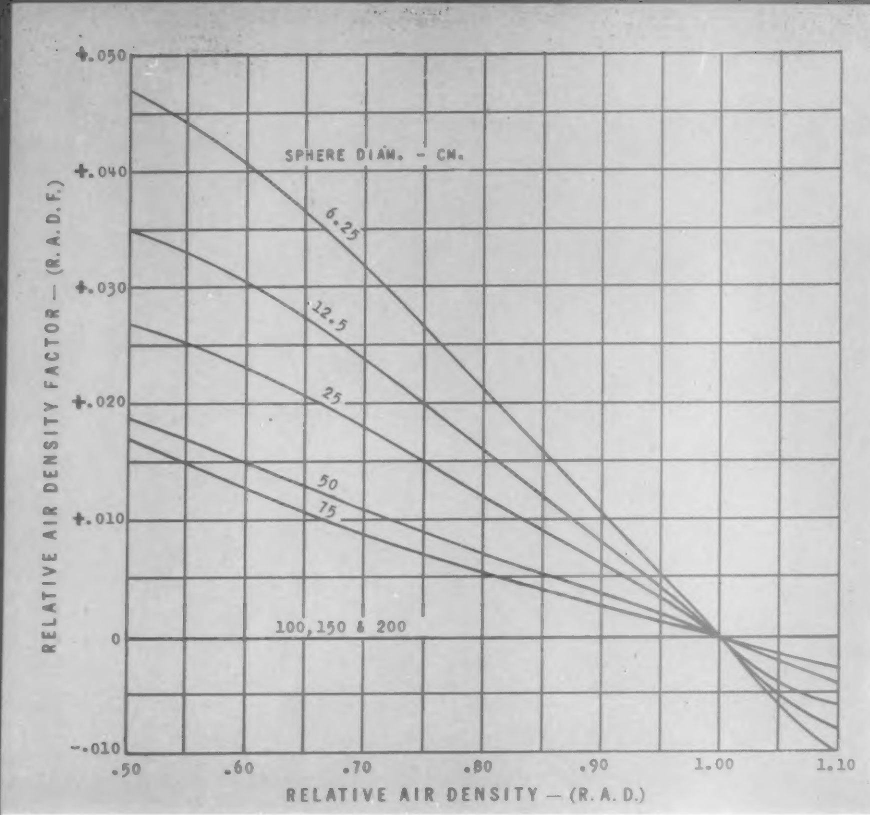


BAROMETRIC CORRECTION is obtained by finding the intersection of the barometric pressure and the wet bulb depression. Value is read from the family of curves, interpolating if necessary. **(FIGURE 2b)***



WET BULB CORRECTION is determined by finding the intersection of wet bulb temperature and wet bulb depression. Read value from the family of curves shown above, interpolating if necessary. **(FIGURE 2c)***

***ACTUAL VAPOR PRESSURE** can be obtained by adding the results of Figures 2a, b and c, observing the sign of the correction factors.



RELATIVE AIR DENSITY correction factor for a sphere gap is found by entering the curve at the value of the relative air density and proceeding until the appropriate sphere diameter is reached. At this intersection, correction factor is read from scale at left. (**FIG. 3**)

Use: Figure 2b. Correct for the actual barometer reading by finding the correction factor at the intersection of 28.95 inches and the wet bulb depression (t-t′), (62-46) = 16 degrees. The correction is + 0.009 (to the nearest .001).

Use: Figure 2c. Correct for the actual wet bulb temperature by finding the correct factor at the intersection of the wet bulb temperature, 62 degrees F and the wet bulb depression, 16 degrees F. The correction is —0.002 (to the nearest .001). Add the three figures together to get the vapor pressure, 0.137 + (+0.009) + (—0.002) = 0.144 inches.

3. To find sphere gap sparkover

Given: A pair of 50 cm spheres. Gap = 15 cm. Under standard conditions, sparkover occurs at these crest voltages.

60 Cycle and Negative Impulse = 367 kv
Positive Impulse = 374 kv

RAD = 0.920

Use: Figure 3. Find the density correction factor corresponding to RAD = 0.920. This is (0.920 + .003) = 0.923. Refer to Equation 3. Let H = 1.0 so $V_t = V_sD$. The gap will spark over at these test voltages.

60 Cycle & (—) Impulse = 367 x .923 = 339 kv
(+) Impulse = 374 x .923 = 345 kv

4. To find sphere gap spacing for a specified sparkover voltage

Given: A pair of 100 cm spheres to sparkover at 325 kv, rms when the RAD = 0.913.

Use: Equation (3) to find the standard voltage at which the spacing must be set.

$$V_s = \frac{325}{.913} = 356 \text{ kv}$$

Reference to sphere gap sparkover data shows a 20 cm spacing is required.

5. To find sparkover voltage of a sphere gap referred to standard conditions

Given: The actual test sparkover voltage of a certain gap when using a 75 cm sphere is 230 kv., rms RAD = 1.05.

Use: The relative air density correction factor from Figure 3 is (0.96 — .001) = 0.959 from Equation 3.

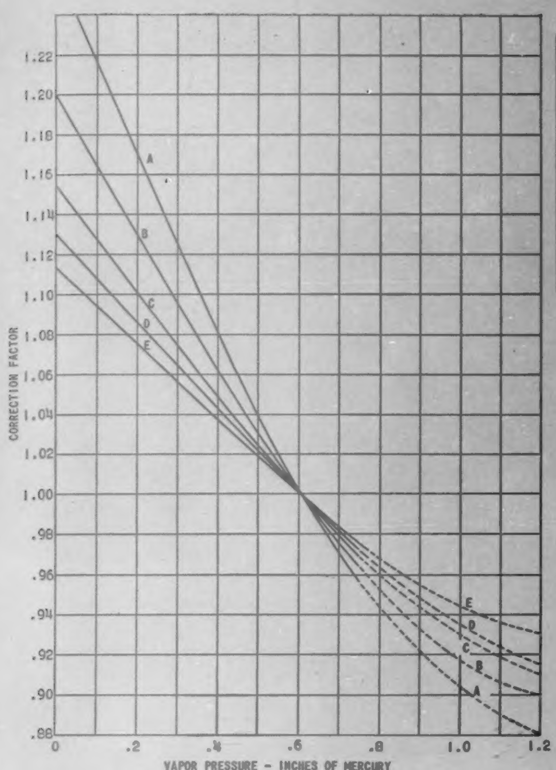
$$V_s = \frac{230}{0.959} = 240 \text{ kv}$$

6. To find the actual rod gap or insulator sparkover

Given: The critical sparkover of a certain rod gap under standard conditions is 750 kv, crest, when tested with a 1½ x 40 microsecond negative wave. RAD = 0.98 and VP = 0.39 inches.

Use: Figure 4 gives the humidity correction factor under these conditions as 1.042. Equation 3 then gives:

$$V_t = \frac{750 \times 0.98}{1.042} = 706 \text{ kv}$$



HUMIDITY CORRECTION FACTOR is found by entering the curve at the value of the vapor pressure and proceeding until the appropriate curve is reached as designated by the classification in the box. At this intersection the correction factor is read from the left-hand scale. **(FIGURE 4)**

UNIT	60 CYCLE	1½ x 40 IMPULSE POSITIVE	1½ x 40 IMPULSE NEGATIVE
Pin Type Insulators	A	D	E
Rod Gaps	B	C	D
Suspension Insulators	B	C	D
Switch and Bus Insulators	B	D	E
Roof, Floor, and Wall Bushings	B	D	E
Apparatus Bushings — Gapped	B	C	D
Potheads	B	D	E

7. *To find the rod gap or insulator critical sparkover voltage at standard conditions*

Given: The critical sparkover voltage from test is 810 kv, with a $1\frac{1}{2}\times40$ microsecond, positive wave. RAD = 0.97, and VP = 0.20.

Use: Figure 4 shows the humidity correction factor to be 1.10. Equation (3) then gives:

$$V_s = \frac{810 \times 1.10}{0.97} = 919 \text{ kv}$$

8. *To find the actual rod gap or insulator sparkover at 4.0 microseconds when the time to critical sparkover is greater than 10 microseconds*

Given: The 4.0 microsecond sparkover voltage under standard conditions is 890 kv, crest, when tested with a $1\frac{1}{2}\times40$ microsecond negative wave. RAD = 0.98 and the VP = 0.39 inches.

Use: The full humidity correction factor from Figure 4 is 1.042. The effective humidity correction factor at 4.0 microsecond:

$$H' = (1.042-1.0)\frac{40}{100} + 1 = 1.017$$

The actual 4.0 microsecond sparkover voltage is:

$$V_t = \frac{890 \times 0.98}{1.017} = 857 \text{ kv.}$$

9. *To find the rod gap 2.0 microsecond sparkover at standard conditions where the time to critical sparkover is less than 10 microseconds, and the crest voltage is less than 141 kv.*

Given: The 2.0 microsecond sparkover by test is 122 kv, with a $1\frac{1}{2}\times40$ microsecond, negative wave. The time to critical flashover = 8.0 microseconds. RAD = 0.97 and VP = 0.20.

Use: Figure 4 shows the correction factor to be 1.10 under the conditions given. Reduce the humidity correction factor in proportion to voltage by reference to Equation 4.

$$H' = (1.10 - 1.0)\frac{122}{141} + 1 = 1.087$$

Further correct this humidity factor for time to flashover, thus:

$$H'' = (1.087 - 1.0)\frac{2.0}{8.0} + 1 = 1.022$$

From Equation 3 the 2.0 microsecond sparkover voltage, if standard conditions prevailed, would be

$$V_s = \frac{122 \times 1.022}{0.97} = 129 \text{ kv}$$

10. *To find the $1\frac{1}{2}\times40$ microsecond, positive, critical sparkover of a string of suspension insulators at 10,000 feet altitude*

Given: The barometric pressure at 10,000 feet and 77 degrees F is 21.0 inches and VP = 0.20. The critical sparkover level of the insulators at standard conditions is 740 kv.

Use: Equation 1a gives the relative air density as:

$$RAD = \frac{17.93 \times 21.0}{459 + 77} = 0.702$$

The humidity correction factor from Figure 4 is 1.10. Using Equation 3 the critical flashover is:

$$V_t = \frac{740 \times 0.702}{1.10} = 472 \text{ kv}$$

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Care of AC Rotating Equipment

PART THREE OF FOUR PARTS

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Prompt machine repair saves time, money and production.

MACHINE REPAIR is a continuation of maintenance. Even the best of care cannot keep a machine going indefinitely. Like the human body, it is limited in capacity, and component parts eventually wear out because of continuous use even under the most favorable operating and maintenance conditions.

This phase of maintenance, therefore, concerns itself with emergencies requiring immediate attention to avoid production losses. For example, a vital motor-driven pump highly important from the standpoint of smooth production flow must be maintained by regular and thorough inspections, cleaning, etc. However, if the motor breaks down the maintenance department must make immediate repairs or replace the machine to continue production. Common sense, promptness and a little foresight can eliminate many consequences of machine breakdown.

One of the primary requirements of prompt and efficient servicing of rotating equipment, for any type of machinery for that matter, is an adequate reserve of spare parts where machine size and economy permit.

Oftentimes the bearings and bushings on each end of a machine are duplicate so that it is only necessary to keep one spare bearing for such machines.

In addition, a complete set of brushes should be stocked for slip ring type induction motors and synchronous machines.

Stator coil repairs protect core

As the air gap of induction motors is relatively small when compared to other types of machines, it is most important that the bearings of such equipment be kept in good condition at all times. If a bearing fails in operation and allows the rotor to rub the stator, it creates hot spots in the stator and rotor cores that may eventually break down the slot insulation and cause a ground or short circuit in the coils that may possibly damage the core of the machine sufficiently so that it has to be completely rebuilt. Such breakdowns may seriously hamper production because of the magnitude of the repairs required.

Where the iron laminations are not too badly affected, temporary repairs to coils may often be possible. Such repairs may extend to cutting a number of the damaged coils out of the winding entirely. In multi-circuit windings, coils should be cut out of the other parallel circuits of the same phase in order to prevent internal circulating currents.

Many engineers recommend cutting symmetrically-placed coils out of the other two phase windings in a three-phase machine to obtain phase balance. Usually this is needed only if the neutral is grounded. Repair of this sort is merely a temporary expedient for emergency use only, and is not recommended for general practice. Often this measure will avoid serious production difficulties until more time is available later to provide new coils to replace the damaged ones. Ordinarily, spare coils are not kept for small or fractional horsepower machines, since it is often more practical to replace a fractional horsepower motor entirely. Usually, coil replacements for other small and medium sized machines can be obtained on fairly short notice.

Repairing slip ring rotors

If breakdowns occur on the slip rings or brushholder insulating spacers or tubes of a slip ring type induction motor rotor they should be replaced. It is good practice to keep the creepage surfaces on these parts clean to avoid troubles due to voltage flashovers and breakdown.

When solder runs out of the clips at the ends of the rotor windings without resulting in other damage, the clips should then be resoldered and the load decreased when operation is resumed. Any sign of solder flowing in the clips is usually considered a warning to reduce machine loading, especially peak loading. Generally, it is an indication of overloading and the band wire should also be checked for looseness and solder throwing.

Failures in rotors of induction motors should be investigated completely. Often what are at first believed to be coil failures may be breakdowns in the control exterior to the motor, or in the brushholder or slip ring assembly.

When testing a rotor winding, it should be remembered that there are many leakage paths to ground besides the coils themselves. When checking the winding insulation resistance, it is a good policy to raise the brushes, or disconnect the winding leads at the slip ring assembly or even near their connecting joints at the phase ends of the winding itself to obtain the true winding insulation resistance.

In cases of definitely established coil failures, the coil or coils will likely have to be removed for repair or replacement. Coils cannot be conveniently cut "dead" for emergency operation where the "wave" type of windings are commonly used, such as in rotors of slip ring type induction motors.

Rebabbitting is usually necessary when bearings have seized or wiped. When spare bearing bushings are available, the machine can be quickly restored to service, provided there has been no serious damage from such causes as the rotor and stator rubbing, shaft scoring, bent shafts, etc. It is well to check such points before putting the machine back into operation. A new bearing shell or bushing should be provided with fresh oil and have perfectly operating oil rings.

Rotor-stator rub shorts laminations

Iron (eddy and hysteresis) losses in electrical machines can be reduced considerably by laminating the magnetic paths carrying alternating fluxes. However, in machines which have

MODERN REPAIR facilities are maintained by some manufacturers for breakdowns beyond the scope of shop maintenance. These reliable services are only as far as the nearest telephone.

small air gaps, and this is especially true of induction motors or generators, too much bearing clearance, vibration transmitted from driven equipment, eccentricity of the rotor in the stator causing uneven air gap around the bore, and, therefore, unbalanced magnetic pull around the rotor may cause the rotor to rub the stator and short the core laminations. Large losses may occur at the shorted parts and the high localized temperatures may quickly damage the adjacent coil insulation. Any suspicious warning, however vague, such as occasional sparks in the gap or machine noise, vibration or throbbing should be immediate cause for shutting down the equipment and investigating its source.

If the shorted laminations are not badly burned or gouged, the core can be loosened and the sharp edges of the rubbed portions of the laminations can be separated by filing. Whenever possible, the affected laminations should be removed entirely so that they can be handled more easily and enameled for restoration to their former condition. But in a serious emergency the rotor can be removed and the core need merely be loosened to permit filing of shorted edges of the laminations. Thin paper spacers can then be inserted between alternate punchings. If slot sticks have been charred by the heat developed by shorted laminations, they should be replaced. Before doing so, however, it is advisable to examine the coil insulation carefully for possible damage.

Replacing complete machines

Because smaller machines are pretty well standardized as to their General Purpose Application, type and classification, the possibility of error in replacing them is virtually nonexistent. Most of the larger machines are beyond the General Purpose Ratings and are apt to be "tailor-made" so that extreme caution should be exercised in their application. In extreme emergencies the maintenance department cannot be too selective at times. But certain mechanical and electrical precautions can be observed.

Some of the mechanical considerations which should be extended in replacing machines for emergency purposes are both simple and effective. For instance, if an open type machine is replacing a splash-proof or drip-proof machine some method of protection against dripping or splashing material should be installed. It may consist of sheet metal or other type of cover placed over or alongside the motor.

An indoor machine should not be placed outdoors for operation except in most serious emergencies. These machines are not weather-proofed for outdoor operation. Whenever an emergency warrants using such equipment, a weather-proof covering or housing should be used to prevent moisture from being taken directly into the machine windings. In addition, space heaters should be available to prevent windings from absorbing moisture when the machine is shut down.

Electrically, of course, a machine should not take more starting kva at a lower power factor from the line than the one it replaces, unless it is known in advance that no adverse results will be obtained from such additional kva requirements.

Many special installations require not only an ample power supply but also large starting and accelerating torques. Such applications require motors with considerable built-in thermal capacity to provide safe acceleration. It is wise to have records of such equipment or consult the manufacturer so that a replacement motor not possessing the proper qualifications will not be damaged because it is not being properly used.

Ingenuity helps

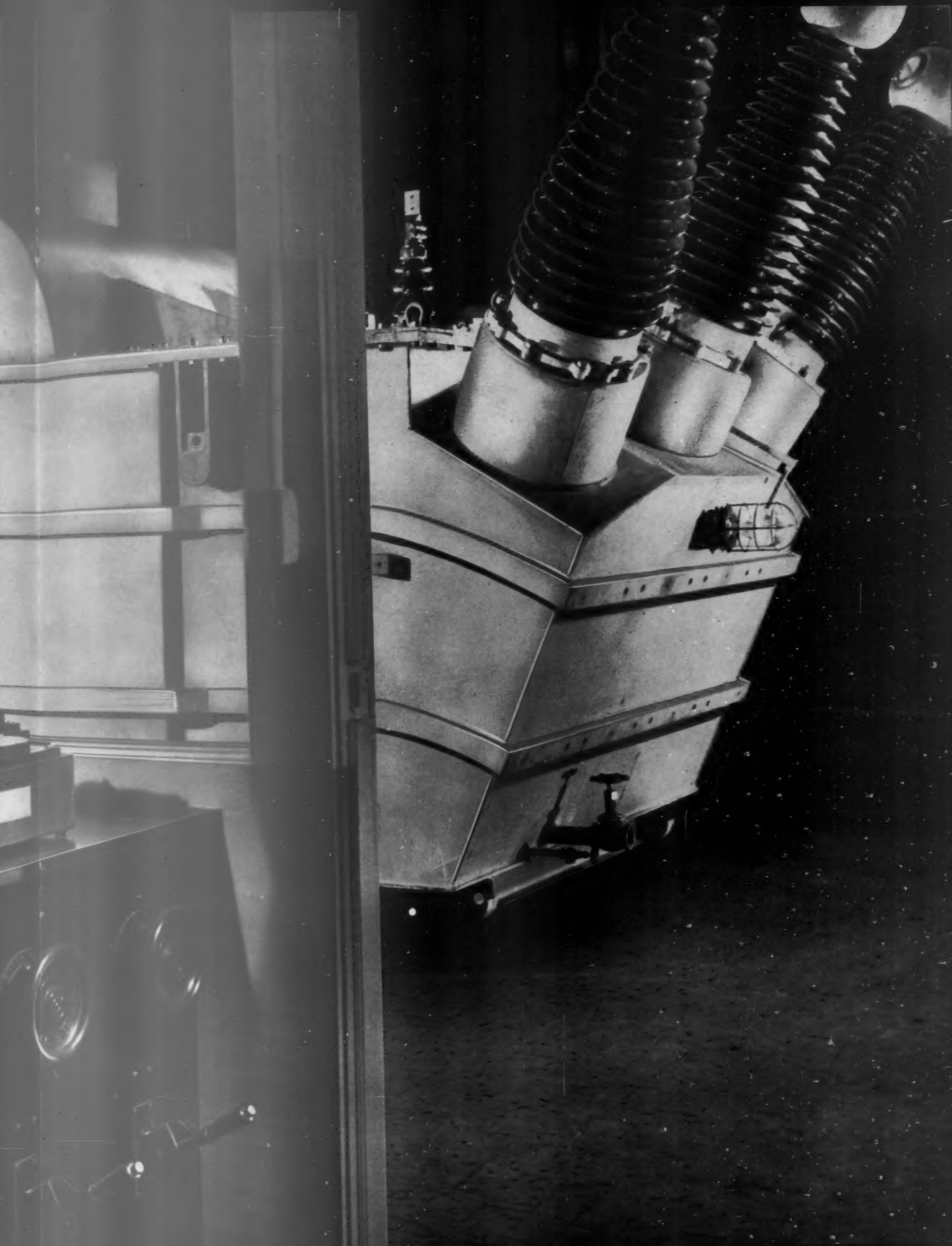
There are times when motor breakdown cannot be immediately remedied by replacement simply because many motors are usually not readily available. Many times even relatively prompt motor delivery does not remedy the situation. It is then that the maintenance department must make the best of whatever suitable materials it has at its disposal.

For example, some old two-phase machines may be used for three-phase operation by simple reconnecting or rewinding. Occasionally, machines can be reconnected for the next higher or lower synchronous speed. While reconnecting for different voltages may often be possible it should be done only with definite knowledge and understanding of motor design characteristics. When in doubt as to just what a given available motor can be used for or how it can be revamped, the manufacturer should be supplied with name-plate data and the desired rearrangement of motor characteristics.

Machine repair—the right way

The maintenance department should keep a record of each piece of equipment much like a doctor maintains a file of his patients. A simple card file system is the most practical and efficient way of recording the machine's history. A systematic record of the machine's history and its repairs, especially as to kind and frequency of repair, can help anticipate and often prevent loss of machines. More important is the prevention of production loss.

NEW TEST FLOOR for large power transformers is one of the most modern in existence. Centralized meters and controls facilitate complete tests from control room. Tester is preparing for a heat run on a 110-kv mobile substation transformer.



SYSTEM TROUBLE!

PART ONE OF
TWO PARTS

W. E. SCHWARTZBURG and R. P. HOLLAND
Switchgear Section
Allis-Chalmers Mfg. Co.

Alarm tells when, annunciator shows where trouble occurs . . . combination means better system protection.

THE NIGHT OPERATOR of the John Doe generating station rose slowly from his well-padded chair. It was time to fill in the second shift log. As he began to make the rounds, slowly recording volts, amperes, kilowatts, and other data, he was stopped suddenly by the shrill bleat of the alarm horn. In a few long strides, he was in front of the annunciator determining what had caused the trouble. A quick glance showed drop 5 indicating the source of trouble — transformer 3 temperature relay had picked up. By pressing the alarm reset push-button, the operator silenced the alarm horn and made preparations to eliminate the cause of trouble. A glance at the meter showed that the load on feeder 3 was exceptionally high. Quickly he transferred the load to a spare transformer so that the transformer which had been overloaded could be cooled off.

What would have happened had there been no annunciator panel to enable the operator to determine the cause of the disturbance? Before the exact source of trouble could have been located, the transformer temperature relay contacts in the breaker trip coil circuit would have, in all probability, closed. Also, the breaker would have tripped, preventing damage to the transformer. However, this operation would have resulted in an outage on feeder 3. This is an example of where prompt action of the operator and use of an annunciator prevented service outage of the particular feeder.

Warning must be positive

Obviously, the annunciator and alarm relays must be positive in action since they are the last barrier between normal operation and the breakdown of expensive equipment. Alarm and annunciator systems are vital to the successful and efficient operation of all types of electrical apparatus. Steel mills, distribution substations, generating stations, rectifier substations, in fact every application of electrical equipment requires careful selection of an alarm system. To the public utility, where continuity of service is paramount in importance, the annunciator and alarm system gives the operator an advanced warning of hazardous conditions before protective relays have a chance to act, thus allowing correction of trouble.

To begin with, an alarm system should not be confused with an annunciator system. Basically, an alarm system will signal to the operator that some undesirable action has taken place. It does not necessarily tell him what caused the trouble, but merely tells him that something has occurred requiring his attention. An annunciator system directs him to the source of trouble, usually before or simultaneously with any automatic action. Thus the latter goes a step further than the alarm system by providing a more detailed indication of what is happening. As the annunciator involves more equipment, it is generally applied where the apparatus being protected is more vulnerable. Thus a simple system might incorporate only an alarm without an annunciator, but any system using an annunciator would also require an alarm.

To be effective, the function and operation of alarm and annunciator schemes should be as simple as possible. When some abnormal condition occurs, the operator can be notified by either visual or audible warning. Where only a limited number of sources of trouble are possible, horns, bells or sirens of various tones can be used in an audible system. However, it is extremely important that the operator is not confused at the time the alarm sounds by requiring him to differentiate between three or four different tones. It is best to attract the operator's attention by some audible device, such as a horn or bell, and then have him refer to a centrally located panel on which the annunciator is located.

Annunciator tells all

By definition, an annunciator is a device operating by compressed air or electro-magnetism to show a number, name, etc., when a corresponding bell is rung. It is also the dial or board on which the signal transmitted is displayed. To the station operator, the annunciator usually consists of a series of amber lights or numbered drops. To the engineer responsible for the design and application of the equipment, the annunciator system represents a group of control and auxiliary relays which must convey the presence of trouble in a simple and reliable way to the station operator's attention.

As stated previously, the annunciator itself can consist of signal lamps or numbered drops. However, lamps are usually preferred since there is no chance of mechanical failure as exists in the common and familiar annunciator drop. When using lamps for indication it is sometimes considered desirable to have the lamp lit when the operating function is normal and extinguished when trouble occurs. This draws immediate attention to a defective lamp. Of course, almost all annunciator panels with lights that burn when the protective relay picks up, or when trouble occurs, are equipped with a test push-button, which energizes all lamps so that defective bulbs can be replaced.

Location of the annunciator system is very important. It should be placed in a convenient and readily visible position. The initial installation of any warning system should be carefully considered so that when additional circuits or equipment are added there will be adequate room on the centrally located panel. When adding circuits to an alarm system, great care must be taken to make sure the scheme is fool-proof and that

WHERE?

the added functions will not confuse the operator. Therefore, when planning a control panel, make certain there is plenty of room, both physically and electrically, if there is any possibility of additional future circuits. It may be found more economical to anticipate future system functions and provide blank identification plates which can be filled in later.

The alarm bus is energized by the mechanical or electrical relay which is supervising the operation of the protected equipment. Much has been written about relaying and it is universally recognized as an important field of study by the electrical industry.

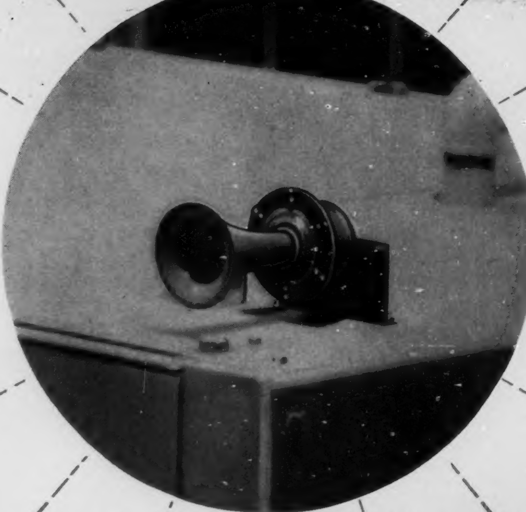
Primary relay protection essential

Understanding the average power system's relay requirements helps considerably in providing an efficient and adequate alarm system. First of all, to properly protect any piece of equipment it must be known what conditions can occur and what must be done to correct them.

The typical generator, as a rotating piece of equipment, is vulnerable to a number of different types of trouble. If the prime mover can drive the generator at dangerous overspeeds, or if the generator and its prime mover can be driven by another machine at dangerous overspeeds, then the generator should be equipped with either a direct-connected mechanical device on the shaft of the machine or an overfrequency relay. The generator set should be protected from excessively high temperatures which can injure or shorten the life of the machine. Bearings, as well as the stator, should be protected from dangerous temperatures. In an unattended station, such as a hydrogenerating station, the temperature relay must automatically reduce the load or shut the unit down as well as give a remote alarm to the supervisory station. However, in an attended station the temperature relays normally have two sets of contacts operating at different temperatures, the low temperature contacts being set to provide only an alarm. The high temperature set of contacts disconnects the equipment.

Electrically, the generator may be equipped with relays to guard against overcurrent, short circuits, under and over voltage, single phase and unbalanced current operation, and motoring of the generator. Relaying depends on the system, size of the unit, and other factors. Generator relaying is much more complex than the relays supplied on a transformer which, as a static device, is normally subject only to short circuits, open circuits, overloads and voltage surges. Differential relays, ground relays and temperature relays are commonly supplied on large transformer installations. Again the size and application of the transformer bank determines what relays are to be used.

For example, if the transformer is equipped with circuit breakers in both the high and low voltage sides, differential relays are recommended on banks of a 1,000 kva or larger; on transformers of 5,000 kva or greater capacity, circuit breakers should always be placed in the high and low voltage lines and the transformer should be protected with differential relays. However, here again an unusual application would cause the application engineer to take exception to this general rule.



The complexity of properly protecting a utilities transmission, subtransmission and distribution circuits varies with the capacity, length, and voltage of the circuit in question. Each type of protection has its own field of application — from the common fuse to the expensive and intricate carrier-pilot relay circuit breaker scheme. Buses, as well as lines, must be protected since the bare buses may be short-circuited by foreign material. Of course, metal-clad switchgear has gone far to eliminate this common source of trouble.

Protective relays spot trouble

Besides generators, transformers, lines and buses, large motors and rectifiers must be properly relayed. Protective relaying is important in the application of every type of electrical machinery as it directly affects the quality of service and represents insurance on the investment in the machinery.

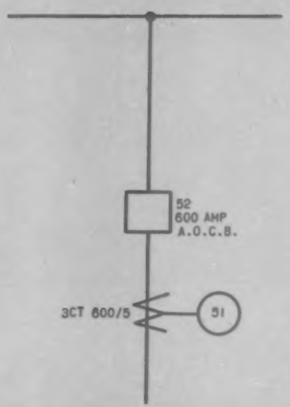
When trouble occurs, the operation of the protective relay must be indicated. In an electrically operated relay, this is usually accomplished by a target built into the relay itself. In many instances, this is supplemented by a signal on the switchboard. For instance, if one of the three overcurrent relays protecting a feeder closed its contacts, the target in one of the relays would pick up, the alarm horn would ring, annunciator light would become energized, and the trip coil of the breaker would be energized. As soon as the operator had silenced the alarm and found the group of relays that had initiated the alarm, he could immediately determine which specific relay had picked up by examining the targets of each of the three individual relays. Perhaps the easiest way to show what actually happens is to examine a typical control scheme. For standard symbols used in illustrations, see Table I.*

TABLE 1

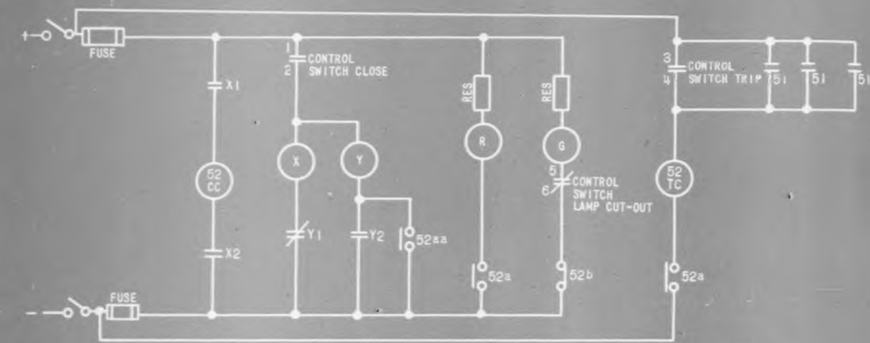
STANDARD SYMBOLS

Symbol	Item
51	A-C overcurrent relay
52	A-C circuit breaker
CS	Control switch
TC	Trip coil
CC	Closing coil
a	Auxiliary switch closed, when breaker is in energized position.
b	Auxiliary switch closed when breaker is de-energized
aa	Closed when operated mechanism of circuit breaker is in energized position

* A.S.A. bulletin, Graphical Symbols for Power Control and Measurement can be obtained by writing to the ELECTRICAL REVIEW.



SINGLE LINE diagram showing a 600-ampere oil circuit breaker, "52," with three current transformers and three overcurrent relays, "51." Schematic is shown in Figure 2. **(FIGURE 1)**



SCHEMATIC DIAGRAM of circuit breaker control scheme without alarm. This scheme does not provide the operator with an audible alarm when trouble occurs. However, the red light "R" becomes energized when the breaker is open, giving a visual signal of distress. Upon inspection, operator can determine by the position of targets on the "51" relay whether breaker has been tripped by one or all of the overcurrent protective relays. **(FIGURE 2)**

When examining the schematics it should be remembered that all relays, switches and breakers are shown in the de-energized position. Thus if a contact of a relay is shown in the closed position then the contacts of the relay will be opened when the operating coil of the relay is energized. When examining a schematic diagram, one should familiarize himself with the list of equipment being supplied so that he is acquainted with the operation of the relays and switches. He should also study the manufacturer's wiring diagram of the relay in question as well as the description of the operation of the relay.

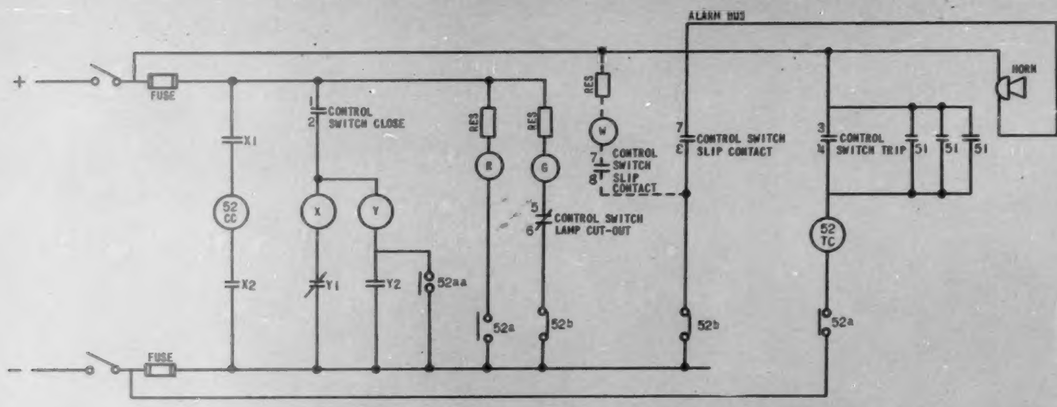
Common alarm schemes

The most common application of an alarm system is in the control of a circuit breaker. This makes sense since the automatic operation of the breaker, when actuated by a protective relay, whether it be an overcurrent, differential, voltage, or directional overcurrent, indicates that some action has taken place and that something must be done by the operator. Therefore, since the alarm is quite often part of the breaker control, let's examine typical breaker control schemes to see how the alarm is incorporated. To more clearly show the difference between a breaker with and without an alarm we will begin by examining breaker control without alarm.

The single line diagram is shown in Figure 1 while the schematic is shown in Figure 2. This common control scheme, often referred to as the "X-Y" scheme, is also known as an "anti-pumping" circuit. To close the breaker, the circuit breaker control switch is moved to the close position. Contacts 1-2 close, energizing the X relay coil. The normally open contacts of the X relay (X1 and X2) then close, energizing the closing coil (52cc) of the breaker. When the circuit breaker has reached its fully closed position the "a-a" auxiliary contacts (52aa) on the circuit breaker (these contacts are mechanically connected to and follow the movement of the breaker mechanism) close, thereby energizing the Y relay coil. The Y contacts of the Y relay instantly de-energize the X relay by opening contact Y1 and keeps it de-energized as long as the operator holds the control switch in the close position. This prevents the circuit breaker from reclosing into a faulted circuit since the closing relay X is held de-energized. To make the second attempt to close the breaker the operator must return the control switch to the off position before the closing coil can again be energized. The importance of this feature, known as anti-pumping, is realized when we consider the rapidity with which a circuit breaker may close and open. In fact, the mechanism could operate several times before the operator could remove his hand from the control switch.

The X-Y control scheme is a simple and reliable method of closing an electrically operated breaker. Now let's consider the relays discussed earlier and how the circuit breaker can be tripped and supply the operator with necessary alarm. As can be seen in Figure 2 when 51, an overcurrent relay, picks up, the trip coil is energized and the red indicating lamp goes out. When the breaker reaches the open position the trip coil (52TC) circuit is opened through the use of an "a" switch (52a) on the breaker and the green indicating light is lit. Note that this control scheme does not provide any form of alarm when the breaker is tripped by the protective relays. In other words, the operator would not be notified in any way except by the red light.

Figure 3 shows a simple method of adding an alarm bus through the use of an additional stage (contacts 7 and 8) on the control switch. By utilizing contact 7-8 an automatic alarm is given whenever the breaker is tripped by the protective relays. Contact 7-8 closes when the control switch is moved to the closed position and remains closed after the control switch returns to the off position by the spring return. If the circuit breaker is tripped by the action of the protective relays, the alarm circuit is energized due to the closing of the auxiliary "b" switch on the breaker. This may be analyzed more closely by following the circuit from the negative side of the control circuit marked N, through the 52-b contact, through the 7-8 control switch contact, making the alarm bus negative sounding the alarm. To silence the alarm all that the operator must do is to move the control switch to the trip position which will open contact 7-8 and de-energize the alarm bus. The second set of 7-8 contacts (shown dotted) are sometimes used to give visual indication on a white light that the breaker has tripped automatically.



SCHEMATIC DIAGRAM of circuit breaker control scheme shown above is similar to that shown in Figure 2, with the exception of the added alarm bus. By using the control switch slip contact the operator is given an audible alarm signal when the circuit breaker is tripped by one of the protective relays, "51." When both the green and white lights are lit, the operator knows that the breaker has been tripped by one of the protective relays. **(FIGURE 3)**

The advantage of this system is its simplicity. It is foolproof when the circuit breakers are opened and closed electrically at all times. However, it should be pointed out that the scheme has several disadvantages. First, when the circuit breaker is closed the alarm horn will sound momentarily because the 7-8 contact of the control switch closes before the "b" switch of the breaker has had a chance to open. Also if the circuit breaker is closed with the emergency handle and the operator forgets to move the control switch to the close position, the alarm circuit will be opened, since contacts 7-8 are open. A subsequent automatic operation of the breaker will not sound the alarm. Some circuit breaker control switches have a red and green target to indicate disagreement between the breaker position and control switch operation to protect against this condition.

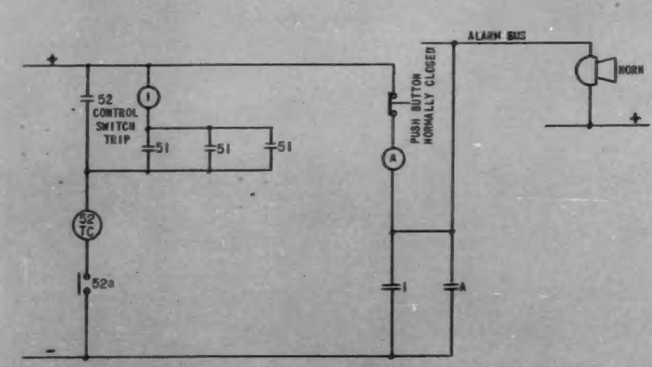
Alarm scheme is flexible

By the addition of still another stage to the breaker control switch, the disadvantage of having the alarm sound while closing the breaker is eliminated. This is accomplished by inserting another stage to the control switch (contacts 9-10, normally closed). The contacts remain closed at all times except during the movement of the control switch in either direction, thereby causing the alarm circuit to be momentarily opened and preventing unnecessary operation of the alarm. This system, however, becomes exceedingly complex where there is more than one control point per breaker.

The extra contacts in the control switch can be eliminated by using an alarm scheme sometimes referred to as the impulse relay method. Shown in Figure 4, this method places all the protective relay contacts in series with the operating coil of the impulse relay "I". Consequently, the operation of any protective relay will energize the impulse relay, which has a normally open contact. This contact will close, energizing the common alarm relay "A", which also has a normally open contact. This contact in turn will close and sound the alarm and seal itself closed. The alarm will continue to sound after the circuit breaker has opened until the operator releases the alarm relay by pushing the push-button "PB".

These are typical examples of simple, inexpensive alarm systems for switchgear and are only a few of the many methods for effective equipment protection. There is no single answer for all emergency alarm problems. The best solution is to select the simplest, most positive scheme which is adequate for a particular system and gives an alarm when trouble occurs. The successful operation of protective relays, circuit breaker and alarm system is extremely important since it represents the last barrier between normal operation and damaged equipment.

ALARM SCHEME showing an impulse relay coil in series with contacts of the "51" protective relays. Alarm bus is energized when the alarm relay "A" is energized, closing its normally open contacts. **(FIG. 4)**



Fundamentals of AC

PART SIX OF SIX PARTS

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Modern oil circuit breakers are virtual self-generated hydrogen-blast breakers.

PRECEDING INSTALLMENTS have considered the process of a-c circuit interruption comprising the steps of first drawing an arc and then converting the arc space from a conductor into a nonconductor of electricity. Various interrupting principles employed for converting the arc space into an electrical insulator were reviewed in a general way. Application of certain of these principles to the oilless types of power circuit breakers—namely to air break and air blast breakers — were also discussed. This, the final installment, is concerned with the oldest and still the most important type of power circuit breakers in this country today—the oil circuit breaker. Although invented and first developed over fifty years ago, and being the original power circuit breaker, the oil breaker is still the only type of power breaker available and applied in this country for all standard ratings from 25 mva at 2,500 volts up to 5,000 mva at 230 kv. It is also the only type of breaker generally available in this country at the transmission and the higher distribution voltages, 46 kv and above.

The oil circuit breaker has made considerable progress in its fifty years. Various special types have been developed including low oil content and oil impulse breakers, of which more will be said later.

The original plain break tank type, or dead tank breaker shown in Figure 1, is no longer in general use except in the very low ratings, but its direct descendant, the modern high speed tank type oil breaker with arc-enclosing interrupting devices, is a very important part of the picture of American power system protection. Therefore, our principal consideration will be this tank type breaker equipped with arc-enclosing interrupting devices within the main breaker tank.

Oil as an interrupting medium

Before considering the functional and structural aspects of oil circuit breakers, the properties of insulating oil as an interrupting medium should be considered. For the moment let us think of an oil breaker simply as a tank filled with insulating oil in which a pair of cooperating contacts is immersed.

The events that follow immediately upon separation of a pair of cooperating contacts which are immersed in a liquid are affected by the speed of contact separation and the viscosity of the liquid. Relatively low speed of contact separation and relatively low viscosity tend to permit the liquid to surround the arc closely at the instant of its inception. Where both the speed of contact separation and the viscosity of the liquid are relatively high, these factors combine to permit the formation of a gaseous tunnel in the liquid which separates the arc at the instant of its inception from the surrounding body of liquid. Such a tunnel constitutes an insulating means which tends to impede interaction between the arc and the liquid. Depending upon the circumstances of the particular case, the formation of such a gaseous insulating tunnel may or may not significantly affect the process of quenching of the arc by the surrounding liquid.

Wherever, as in any oil type power breaker, the heat generated by the arc is high, the liquid surrounding the arc is rapidly vaporized and decomposed. This results in the formation of an arc-surrounding bubble of vapor and gas, which is substantially spherical in shape, if unrestrained. The story of the inside of that bubble is the inside story of the oil circuit breaker. So far as the plain break oil circuit breaker is concerned, its inside story is a plain bubble story, i.e. that of an arc bubble not subjected to the action of means tending to intensify the flow of gases and vapors within the bubble space and to establish a flow of liquid around the bubble. So far as modern oil breakers are concerned, their inside story is that of an arc bubble subjected to the action of special means tending to intensify the flow of gases and vapors within the bubble space and to establish a flow of liquid around the bubble by which the bubble is deformed and constricted.

The bubble formed by an arc drawn through a restricting structure — which is, in effect, an orifice — and subjected to the action of a flow of liquid through the orifice, is often substantially pear-shaped with its constricted end adjacent the outlet end of the orifice. The latter is only partially filled by the bubble. This is the type of arc bubble usually formed in modern oil circuit breakers.

Whether the arc bubble is substantially spherical, as in the plain break oil breaker, or substantially pear-shaped, or of a different or more complex shape, all arc bubbles have certain common features which will be reviewed before considering the distinguishing features of arc bubbles formed in different breaker structures and the different breaker structures responsible for the formation of different types of arc bubbles.

Figure 2 illustrates, diagrammatically, the essential parts of an arc bubble of the kind formed in a plain break oil breaker. The core 1 of the arc extends between a pair of spaced electrodes. While the temperature within the core of the arc is in the order of many thousand degrees absolute, the temperature of the envelope 2 by which the arc core is surrounded is merely of the order of several hundred degrees absolute. The arc envelope is surrounded by an outer zone 3 of superheated vapor which, in turn, is surrounded by a zone 4 of saturated vapor. The bubble wall, i.e. the boundary surface between the bubble and the surrounding body of oil, is in a boiling state. Since the interrupting process lasts not more than a few cycles of the current wave, no substantial rise in temperature of the body of oil takes place remote from the bubble.

Chemistry of the oil breaker

All hydrocarbons, including oils developed particularly for use in oil breakers, decompose under the influence of extreme heat. Such a reaction is generally referred to as "cracking." The

Circuit Interruption

chemical process occurring within the arc bubble is essentially a cracking process. By cracking, hydrocarbons of relatively high molecular weight are converted into hydrocarbons of relatively low molecular weight. The ultimate result of that process may be the formation of carbon and hydrogen in elemental form. Carbon and hydrogen in elemental form are formed in the arc bubble immediately adjacent the arc core where the temperature is highest.

The heat of the arc may convert liquid hydrocarbons into lighter though still liquid hydrocarbons, which may subsequently be cracked to form gaseous hydrocarbons. Fractional distillation of oil which has been used in breakers for increasing periods of time proves progressive formation of light hydrocarbons with continued exposure of the oil to the action of the arc. Formation of light liquid hydrocarbons is limited to portions of the arcing zone situated relatively remote from the arc path. Only gaseous hydrocarbons or hydrogen and carbon in elemental forms are present where the temperature is highest.

The solid carbon formed in oil breakers is in a dispersed state, the dispersing medium being the gases and vapors of which the arc bubble is formed and the surrounding body of oil. Carbon may occur in the breaker oil in varying degrees of dispersion ranging from colloidal carbon to sludge, which is essentially a suspension of coarse carbon particles. Gradual accumulation of carbon can be a source of various troubles. Carbon deposits may impair the dielectric strength of creepage paths of insulating structures and, in extreme cases, interfere with the proper functioning of the breaker mechanism. For such reasons, carbonization of the oil by the arc should be kept to a minimum.

The action of the arc upon the oil produces a chemical compound pertaining to the family of acetylene compounds. The molecules of that compound combine with each other into very large molecules. Such a reaction is known as polymerization. The polymers so formed are a constituent of the sludge that collects at the bottom of breaker tanks.

Aside from hydrogen, the most important gaseous product resulting from the decomposition of oil is acetylene, C_2H_2. The acetylene content of the arc bubble was found to be in the order of 20 percent. Acetylene may be formed by cracking of methane, CH_4, as indicated below

$$2\ CH_4 \rightleftarrows C_2H_2 + 3\ H_2$$

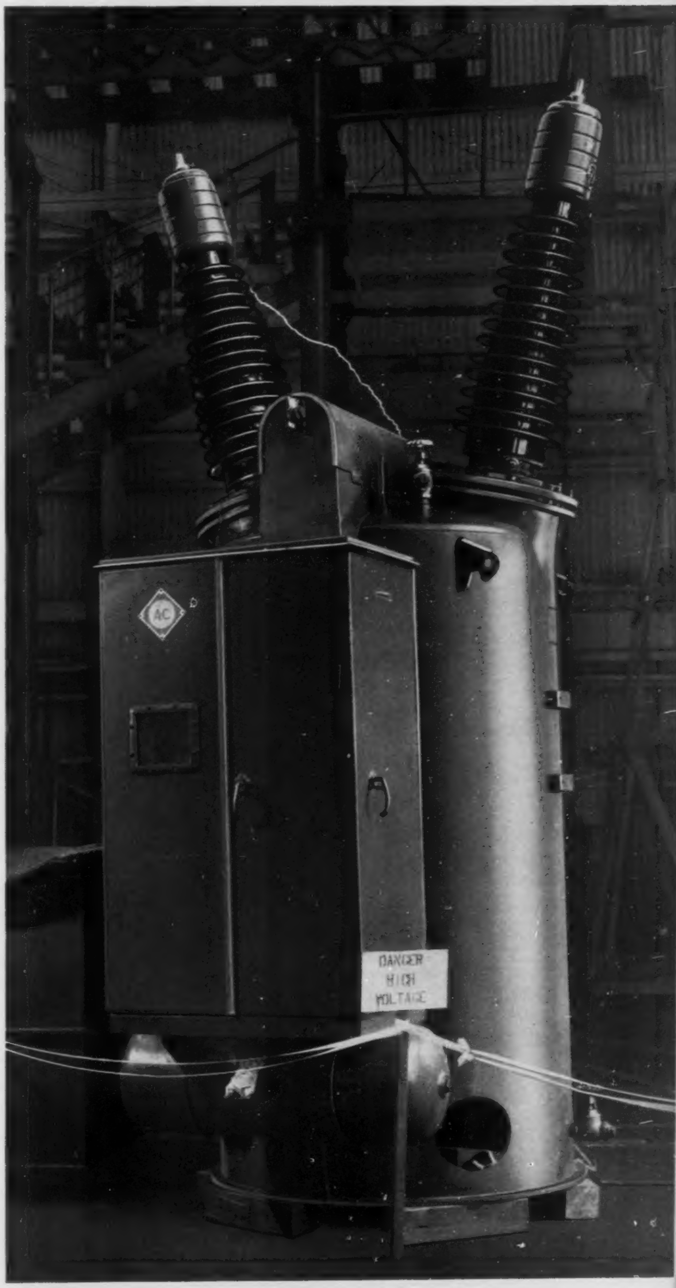
Acetylene is the only hydrocarbon that is stable at arc temperatures in the order of 3,000 degrees C.

Instead of being converted into acetylene, methane may be broken up into elemental carbon and hydrogen as indicated by the following equation

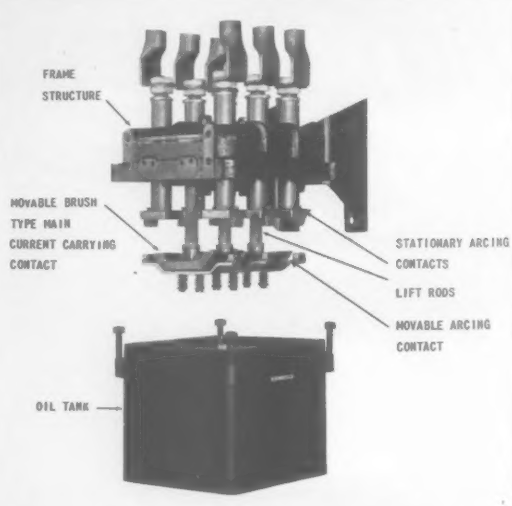
$$CH_4 \rightleftarrows C + 2H_2$$

Molecular carbon and hydrogen may again recombine into hydrocarbons.

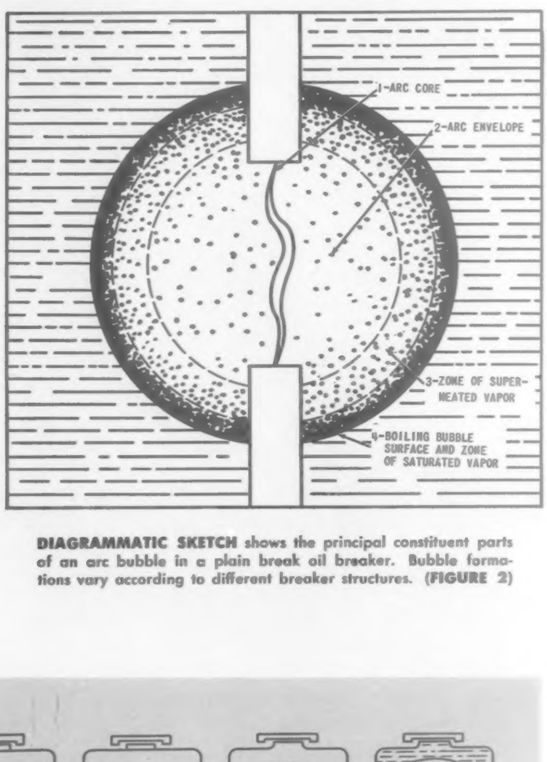
It is important to note that the chemical compounds observed in the bubble may be more or less different from those formed in the bubble during the interrupting process. This is due to the fact that the observed chemical compounds are, or may be, re-formed from their elements or from lighter hydrocarbons.



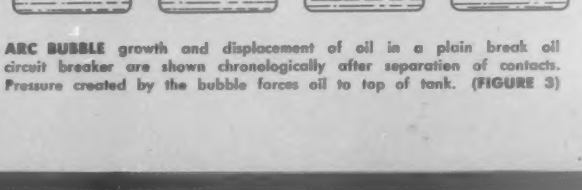
TEST FLOOR VIEW of an impulse flashover test on single-pole of a 161-kv, 1,200-amp, 3,500,000-kva interrupting capacity oil circuit breaker. Note arc from upper end of left-hand bushing to mechanism well cover. Flashover occurred at 835-kv, with a 1½ by 40 microsecond wave. The impulse withstand level for this particular oil circuit breaker is 750 kv.



PLAIN TANK BREAKER shown above is rated 25,000 kva, 800 amp at 5,000 volts. This breaker is one of the few of this type that have not vanished from the circuit interrupting scene. (FIG. 1)



DIAGRAMMATIC SKETCH shows the principal constituent parts of an arc bubble in a plain break oil breaker. Bubble formations vary according to different breaker structures. (FIGURE 2)



ARC BUBBLE growth and displacement of oil in a plain break oil circuit breaker are shown chronologically after separation of contacts. Pressure created by the bubble forces oil to top of tank. (FIGURE 3)

Dissociation of gases

At temperatures as high as those prevailing in the immediate arcing zone, polyatomic molecules will be dissociated. Hydrogen molecules, for instance, will be broken up into hydrogen atoms.

$$H_2 \rightleftarrows H + H.$$

A certain fraction of the gas in the arc bubble is atomic and the rest not, the relation between both portions depending upon absolute temperature and pressure. The energy absorbed from the arc in dissociating polyatomic molecules is released when molecules are re-formed from the atomic gas.

According to Langmuir, at a pressure of one atmosphere, the fraction of molecules of hydrogen dissociated into atoms is

3.71×10^{-9}	at 1,000° abs.
1.22×10^{-8}	at 2,000° abs.
9.03×10^{-2}	at 3,000° abs.
.625	at 4,000° abs.
.9844	at 6,000° abs.
and .9987	at 9,000° abs.

It appears from the foregoing table that dissociation rises rapidly with temperature. At high arc temperatures, a higher percentage of the total arc energy is used for dissociation of polyatomic molecules.

Atomic hydrogen has a higher heat conductivity than molecular hydrogen, which is a factor to be taken into account in evaluating oil breaker performance.

Hydrogen as an arc-extinguishing medium

The total amount of vapors and gases evolved under the heat of an arc depends upon and increases in proportion to arc energy. The arc bubble is formed by a mixture of vapors and gases and its hydrogen content is in the order of 70 percent. Other constituents of the arc bubble are methane, acetylene and other hydrocarbons, carbon dioxide, oxygen and nitrogen. Since the arc bubble consists mainly of hydrogen, the properties and effects of this constituent of the bubble require particular consideration.

A large part of present-day knowledge regarding the arc-extinguishing properties of gaseous media is an outgrowth of research done in the development of the air blast breaker. Originally, compressed air was tried as blast medium, air being the medium most obvious to select and most inexpensive to apply. Subsequently many other gaseous media were tried. The arc-extinguishing properties of compressed nitrogen were found to be equivalent to those of compressed air. Hence there is no point in using nitrogen. Carbon dioxide performed better than compressed air. However, the use of carbon dioxide as blast medium is conducive to freezing of valves and other portions of the blast path. Freon, though expensive, was tried because of its high dielectric strength, but proved to be unworkable because it decomposes under the action of the arc into acid-forming substances. Laboratory tests indicated hydrogen to be the ideal gas for arc extinction. However, the cost of hydrogen blast breakers proved to be prohibitive because of the high cost involved in auxiliary equipment needed for the recovery of hydrogen.

At the time the oil breaker principle was discovered no one knew that arcs drawn under oil form a bubble mainly consisting of hydrogen, and that arcs burning in an atmosphere of hydrogen tend to extinguish more readily than arcs burning in other gaseous media. The discoverer of the oil breaker principle just happened to make a most fortunate choice.

Hydrogen properties affect hydrogen arcs

The dielectric strength of hydrogen stressed up to its rupturing gradient is not particularly high. However, hydrogen has the property of deionizing arcs at a rapid rate and, therefore, the path of an arc in hydrogen recovers its dielectric strength rapidly during each natural current zero. This is the principal advantage of hydrogen as an arc-extinguishing medium.

The burning voltage u_a of an arc is the sum of the voltage drops at the anode, at the cathode and along the positive column of the arc. In high-voltage circuits, arcs of considerable length have but small cathode and anode drops compared to the voltage drop along the positive column. Hence the arc voltage may be considered to be equal to the voltage drop along the positive column. Assuming the voltage distribution along the positive column to be uniform, then

$$u_a = E_a \cdot 1_a \qquad \text{Eq. 1}$$

wherein E_a is the column gradient measured in volts per inch and 1_a the arc length measured in inches.

The outstanding characteristic of arcs in substantially quiescent hydrogen consists in that their voltage gradient E_a is high, much higher than the voltage gradient of arcs burning under similar conditions in air or other gaseous media. Consequently, hydrogen arcs cannot be maintained unless the voltage across the arc gap is high. They do not reignite unless the recovery voltage of the circuit is high.

These singular characteristics of hydrogen arcs are caused by the peculiar characteristics of hydrogen. The specific heat, i.e. the quantity of heat measured in calories required for raising the temperature of one gram of a substance one degree C, is indicative of the thermal properties of any substance. Specific heat depends upon the absolute temperature and any data as to specific heat that are given in the textbooks are averages applicable to a given temperature range. The specific heat of hydrogen is relatively high, i.e. it requires relatively large quantities of heat to raise the temperature of hydrogen (12.5 watt-seconds per gram per degree C has been given as the mean value over the range from 385 degree C to 3,000 degree C). Because of this fact, hydrogen arcs lend themselves relatively well to circuit interruption.

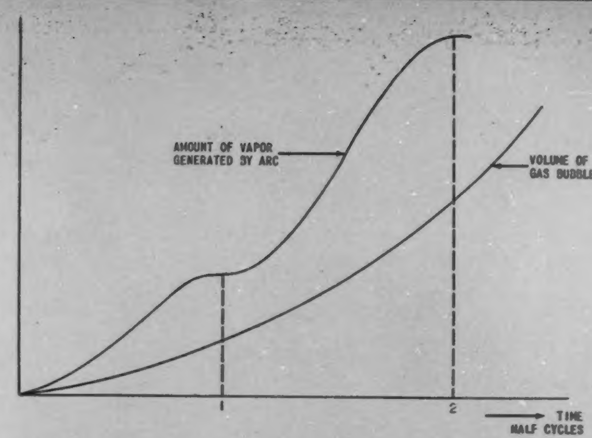
Hydrogen is the element in the periodic system of elements that has the lowest specific gravity or density as indicated in the following table showing the specific gravity of various gases at zero degree C at a pressure of 760 mm mercury.

TABLE I

Gas	Spec. Grav. grams/1000cm^3
Air	1.292 83
Acetylene	1.170 9
Ammonia	0.771 3
Carbon dioxide	1.976 9
Carbon monoxide	1.250 2
Helium	0.178 5
Hydrogen	0.089 87
Nitrogen	1.250 5
Oxygen	1.428 98

The ratio of the weight of equal volumes of oxygen and hydrogen at zero degree C and 760 mm mercury is 15.88 to 1.

As a general rule, the speed at which a gas diffuses increases in inverse ratio to the density of the gas. The speed of diffusion of hydrogen may therefore be expected to be high, as it actually is.



CALCULATED VALUES of the volume of the arc bubble and the amount of vapor generated by the arc in a plain break oil breaker are shown plotted against arcing time. Arc bubble growth is unrestrained. **(FIGURE 4)**

Any gas having a tendency to diffuse rapidly should also have a tendency to rapidly transfer heat by conduction since, by definition, conduction is the process of transfer of heat by diffusion from relatively hot to relatively cool regions. In fact, heat flow is governed by the same law as diffusion. That law may be expressed by the following equation:

$$q = -\lambda \cdot F \cdot \frac{dt}{dx} \qquad \text{Eq. 2}$$

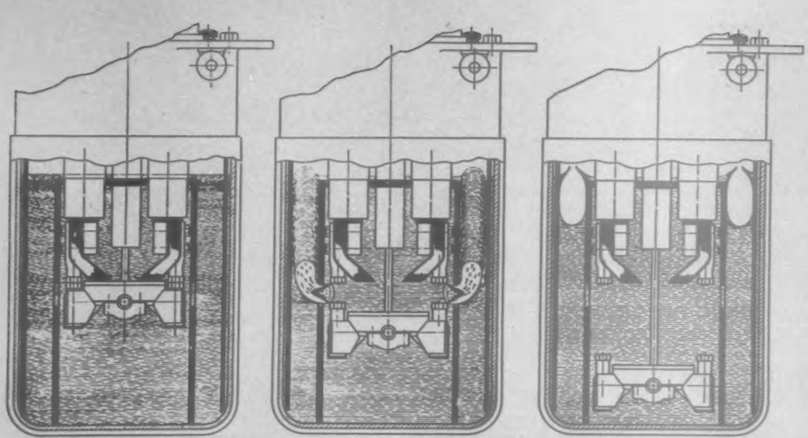
In that equation q is the heat flow in calories per second, F the surface area in square centimeters through which heat flows, dt the change in temperature in degrees C along the distance dx in centimeters and λ is the coefficient of thermal conductivity. The units of λ are calories per centimeter per second per degree C. The thermal conductivity of a gas depends not only upon the nature of the gas but also upon its absolute temperature T. Data as to coefficients of thermal conductivity may be found in textbooks on physics. Suffice it to state here that the coefficient of thermal conductivity of hydrogen is high, resulting in high rates of heat flow and rapid cooling of the path of an arc in hydrogen.

Zero pause within the bubble

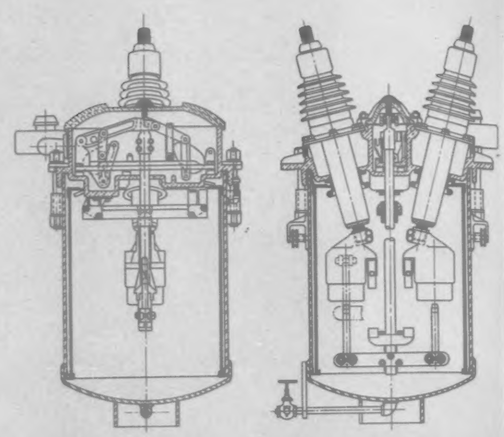
The vapor generated at the bubble walls flows into the arc space proper. Since that vapor is relatively cool and since its flow is highly turbulent, it has an intense deionizing effect upon the arc. This is another reason, aside from the presence of hydrogen, explaining why the voltage gradient of arcs in oil circuit breakers is so high.

During zero pauses of the current wave, the arc energy drops to zero, yet the bubble walls remain in a boiling state. Hence saturated vapor continues to evolve from the bubble walls. That vapor flows turbulently into the residue of the arc, resulting in a rapid increase of the reignition voltage of the arc path. The boiling bubble walls impel even liquid oil particles into the residue of the arc, where such particles are vaporized. The latent heat of evaporation of liquid particles results in a decrease of the temperature of the arc path and an increase of its dielectric strength. The dielectric strength of the arc path is further increased because vaporization of liquid particles results in the formation of clouds of dielectrically unimpaired vapor.

While the arc current is high, the arc is vulnerable only at its surface. No electrically neutral deionizing particle can penetrate right to the core of a high current arc. But during the zero pause, when thermal ionization is at a minimum, the entire arc space, not only its surface, is vulnerable to attack from



BOX-LIKE ENCLOSURE surrounds both pairs of contacts and has only two openings, one adjacent to each pair. This produces an arc-extinguishing blast across the gap formed between the separated contacts. From left to right, drawings show an expulsion port oil circuit breaker closed, interrupting and open. **(FIGURE 5)**



SIDE AND FRONT cross-section views of a specimen of an oil circuit breaker of classic design with stud type arc-enclosing devices shows its functional parts. **(FIGURE 6)**

the outside. Therefore, volume deionization rather than mere surface deionization of the arc space can be effected during the zero pause. It is at this particular point of time that the boiling bubble surface acts to effect penetration in depth of the arc space by impelling into it dielectrically sound vapors and particles of liquid capable of absorbing high amounts of heat. In the plain break oil breaker the invasion of the arc space by electrically sound vapors and by particles of oil is merely a matter of the boiling bubble surface. In modern oil breakers that invasion of the arc space is intensified by the provision of pressure means for driving turbulent streams of vaporized and liquid oil into the arc space.

Bubble forces oil upward

Figure 3 shows, diagrammatically, what happens within a plain break oil breaker after separation of the contacts. Initially, while the contacts are still engaged, the oil is at a given level. As the contacts separate and an arc is drawn, a bubble forms which grows with time. The pressure of that bubble acts upon the body of oil situated above the movable contact, causing that body of oil to rise within the breaker tank. The action of the hot bubble gases upon that body of oil and the resulting displacement of the latter within the breaker tank is similar to the action of the charge of a steam or internal combustion engine upon the piston of the engine and the displacement of the latter within the operating cylinder. For this reason, the term oil piston has been coined with reference to the displacement of the body of oil within a breaker tank. Because of the inertia of the oil piston, it continues to travel and the oil level to rise during zero pauses of the current wave. The oil piston moves and the oil level rises during any zero pause substantially at the same speed as shortly prior to the respective zero pause. This results in continued growth of the size of arc bubbles during any zero pause at substantially the same rate of growth as shortly prior to the respective zero pause.

During zero pauses, the surface of the bubble remains in a boiling state and continues to vaporize, though at a greatly reduced rate. Because the rate of growth of the arc bubble is substantially unchanged during zero pauses while the rate of vaporization is greatly reduced, the rate of growth of the bubble tends to exceed the rate of generation of vapor. Consequently, there is a tendency to decrease of bubble pressure p during zero pauses or, in other words, a tendency toward a negative rate of change of pressure $\frac{dp}{dt}$. Any decrease of bubble pressure results in a more intense vaporization of oil at the boiling bubble surface. Intensified vaporization of oil at the boiling bubble surface causes, in turn, an intensified deionization of the arc residue.

Figure 4 refers to a plain break oil breaker and shows the volume of the arc bubble and the amount of vapor generated by the arc plotted versus time. The rate of growth of the bubble is virtually unchanged and the rate of oil vaporization is considerably reduced during any zero pause.

In modern oil circuit breakers where the growth of the arc bubble is restrained by the presence of an arc-enclosing device, the bubble pressure within the device tends to drive the oil out of the device into the surrounding oil tank. Since arc energy and hence the amount of oil gasified under the action of the arc are minimized in modern oil breakers, the flow of oil out of the arc-enclosing device into the surrounding oil tank results in but a relatively slight rise of the level of the oil within the tank.

Paschen's law and oil breaker operation

In its broadest aspect Paschen's law is to the effect that the breakdown potential of any gas increases with gas pressure and depends upon the product of gas pressure and gap length. Since pressure is an important attribute of the arc bubble and since reignition of the arc within the bubble may take place by way of an electric breakdown, it may be expected that Paschen's law should have a bearing on the operation of oil breakers. This becomes even more evident when considering the reason underlying Paschen's law.

The number of ionizing collisions made by an electron is a function of the mean free path between collisions and the gap length, and the mean free path of electrons decreases with increasing pressure or gas density. Hence the number of ionizing collisions made by an electron is a function of gas density and gap length. Since the breakdown voltage of a gap depends upon the number of ionizing collisions, it also is a function of gas density and gap length.

The breakdown voltage of the arc gap within an oil breaker is not, or not necessarily, a linear function of bubble pressure. It was found as a result of investigations of the dielectric

strength of gases carried on over wide ranges of pressure that there is a linear proportionality between dielectric strength and pressure below a certain limit of pressure in the order of 140 lbs./in.^{2}. Above that limit the rate of increase of dielectric strength with pressure is smaller and the curves representing dielectric strength versus pressure have essentially the shape of parabolas. The rate of rise of the dielectric strength with pressure is different for different gases, as exemplified by the curves showing the dielectric strength of oxygen and carbon dioxide versus pressure which intersect at a certain point.

Since the arc bubble consists of various gases and vapors mixed in different proportions, it is difficult to quantitatively apply Paschen's law to oil breakers.

Distance between arc and bubble walls

The closer the arc to the surface of the bubble, the more intense the action of the surface of the bubble on the arc. The flow of vapor evolving from the boiling bubble surface tends to drive the arc away from that surface. In an oil breaker the arc is generally subjected to electromagnetic forces tending to drive the arc toward the boiling bubble surface. Such electromagnetic forces may be produced either by the action upon the arc of the magnetic field set up by the current under interruption or by the action upon the arc of a suitable magnetic structure arranged close to the arc path. Let B be the force of the vapor blast and M the magnetic force, each acting upon one unit length of the arc. If B exceeds M, the arc will move away from the boiling bubble surface. If M exceeds B, the arc will move toward the boiling bubble surface. If B is equal to M, the arc will be in equilibrium. B increases the nearer the arc to the bubble walls and decreases the more remote the arc from the bubble walls. For any arangement there is a critical position of the arc where it is in equilibrium.

It is desirable to limit the diameter of the bubble in order to keep the surface of the bubble close to the space occupied by the arc core. This can be achieved by various arc-enclosing devices. An artifice for generating vapor close to the space occupied by the arc core irrespective of bubble size consists in arranging highly oil absorbent or porous structures close to the arc path. Oil that is retained by capillary action in a fullerboard structure arranged close to or immediately adjacent the core of the arc will evolve a flow of vapor at the point where such flow is most needed, irrespective of where the bubble walls may be situated.

Elastic vibrations of the arc bubble

The internal bubble pressure decreases progressively as the bubble expands. Finally the internal bubble pressure may be overcome by external oil pressure, causing the arc bubble to recede or collapse. As the volume of the receding or collapsing bubble decreases under the action of external oil pressure, the internal bubble pressure increases again in accordance with the laws of thermo-dynamics. The increasing bubble pressure may become sufficiently high to overcome the pressure of the inrushing oil and to reverse the direction of oil motion for a second time. Such a periodic process is evidently in the nature of an elastic vibration. The frequency at which such vibrations occur depends on various factors, the structure of the breaker in hand, its body of oil, etc.

Elastic vibrations of the arc bubble were also observed in modern oil breakers having an orifice through which the arc is drawn. In such breakers arc-generated pressure on one side of the orifice tends generally to produce a blast of vapors and oil through the orifice. In arrangements of that kind the frequency of the vibrations seems to depend linearly on the maximum flow velocity through the orifice. The frequency of the vibrations may be in the order of a few hundred cycles per second, i.e. several times the 60-cycle frequency of the circuit under interruption. The presence of elastic vibrations accompanied by variations in pressure becomes readily apparent by corresponding periodic changes of the arc voltage. Since the pressure peaks resulting from elastic vibrations of the arc bubble tend to cause an increase of the burning and reignition voltages of the arc, they have also the tendency to inhibit reignition of the arc after a zero of the current wave.

Some quantitative aspects

It is necessary and desirable for a proper analysis of oil breakers to bring some order into the maze of phenomena involved.

We have shown that one of the basic phenomena underlying the operation of an oil breaker is the presence of an atmosphere of hydrogen. It can roughly be determined to what extent the presence of substantially quiescent hydrogen is responsible for arc extinction, where the limit of mere presence of hydrogen lies, and where we must resort to fluid flow to achieve the desired results.

Another method for obtaining a better insight into the working of oil breakers is to apportion the total arc energy among its various components, as indicated in the following table. The data given in that table were found by Bruce, one of the investigators who applied the energy balance method for analyzing oil breaker operation.

TABLE II

	Components	%
1	Contact energy	7
2	Radiation energy	11
3	Energy required to heat and boil the oil	9
4	Energy required to break up the oil	28
5	Expansion of the arc gases	3
6	Raising of gas temperature	39
7	Dissociating hydrogen	3
		100

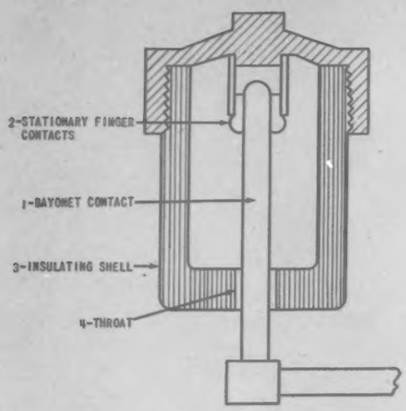
The above energy balance applies only to a particular design of plain break breaker and particular experimental conditions, yet it gives a general idea of some important quantities involved in oil breaker operation. Some of the figures in the table are measured, some estimated, others computed.

The first item, "contact energy," refers to the amount of heat used in raising the temperature of the contacts and in vaporizing contact metal. About 7 percent of the total arc energy is thus absorbed.

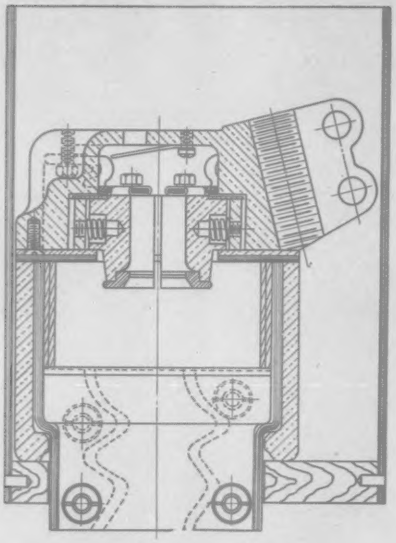
The second item, "radiation energy," refers to that portion of the total arc energy which is converted into radiation. The figure of 11 percent is a rather uncertain estimate of the portion of the arc energy converted into radiation.

The third item, "energy required to heat and boil the oil," covers the energy needed for raising the temperature of the oil from normal to the boiling point (approximately 385 degrees C) and the latent heat of vaporization of oil required for changing its state from that of a liquid into that of a vapor.

The fourth item, "energy required to break up the oil," refers to the energy required for decomposing the oil vapors. It is possible to assume that the arc bubble consists merely of elemental carbon and hydrogen and that the chemical compounds



TODAY'S ARC-ENCLOSING devices were evolved from the plain explosion pot shown in the above illustration. **(FIGURE 7)**



"RUPTOR" INTERRUPTING device with serpentine throat is a younger version of the explosion pot. **(FIGURE 8)**

observed in the bubble are re-formed from elemental carbon and hydrogen. Another possible assumption consists in that the bubble is actually formed by the chemical compounds observed in it. Both cases are theoretical limiting cases and actual conditions within the arc bubble are probably somewhere between these limiting cases. The figure of 28 percent of the total arc energy required to break up the oil is the mean of the two possible limiting cases.

The fifth item, "expansion of arc gases," refers to the work done by the expanding arc products. This item covers mainly the work done by the oil piston in compressing the gas cushion above the oil level on top of the breaker tank.

The sixth item, "raising of gas temperature," refers obviously to the conversion of electric energy into heat consisting in an increase of the thermal agitation of gas molecules and atoms by collisions with electrons which are rapidly moving under the action of the electric field.

If we assume that the chemical compounds observed in the arc bubble are re-formed within the bubble, account must be taken of the energy required to synthesize these gases. Dissociated or atomic hydrogen, when re-forming diatomic hydrogen, releases a certain amount of heat which is available to synthesize the gases observed in the arc bubble.

The seventh item, "dissociating hydrogen," depends upon temperature and pressure within the arc bubble.

Heart of the modern tank type breaker

In plain break breakers the resistance of the arc path is increased at a relatively slow rate. Arc elongation plays a major part in the process of increasing the resistance of the arc path and arc elongation is effected by the relatively slow process of increasing the amount of contact separation. This results in arcing times extending over many half cycles and in correspondingly large amounts of arc energy $\int_0^T u_a \cdot i_a \cdot dt$ in which term u_a is the arc voltage and i_a the arc current. The larger the amount of arc energy, the more elaborate means are required for its dissipation. Both contact and oil deterioration increase in proportion to arc energy and so do the cost and the amount of labor involved in breaker maintenance. Where the interrupting time of a breaker is too long, large rotating machinery may fall out of step and, where such loss of stability of an electric system occurs, the fault cannot be localized any longer and complete interruption of system service results.

All these factors require breakers capable of effecting circuit interruption in shorter times than the plain oil breakers require and involving relatively smaller amounts of arc energy than breakers of that type. In other words, what is needed are breakers wherein the resistance of the arc path is increased during zero pauses at a more rapid rate than in the plain oil breakers, resulting in a decrease of arc energy per half cycle as well as in a decrease of the total arc energy expended during the entire arcing time. These breakers should rely on a means for increasing the resistance of the arc path which is more rapid than arc elongation due to contact separation and be capable of introducing sufficient resistance into the arc path to achieve complete interruption of the circuit at a relatively short gap between the separated contacts.

As previously intimated, the answer to that problem consists in the provision of means tending to establish a more intense vapor and oil flow within the arc space than the boiling bubble surface in its natural state is capable of producing. The first step to this end is to provide a semiclosed subchamber within the oil tank which separates the arcing zone from the main body of oil and tends to restrain the growth of the arc bubble, thereby keeping the bubble surface close to the arc path. Such a subchamber is generally referred to as an arc-enclosing device. The second step is to provide means within the arc-enclosing device for producing a forced flow of gas and oil toward and into the arc path. Such a forced flow can readily be produced by appropriate control of the pressure generated by the arc itself.

The pressure of the gas on the body of oil within an arc-enclosing device and the configuration of the interior of the arc-enclosing device determine the flow of gas and oil within and out of the device and the action of that flow upon the arc. Therefore, the arc-enclosing device is the very heart of any

modern oil breaker. The term "heart of the breaker," however, has a secondary meaning, the problems of arc-enclosing devices being mainly circulation problems. The basic circulation problem consists in compelling the necessary proportion of the gases resulting from the decomposition of oil to flow through the arc path and in limiting the escape of such gases without having passed through the arc path. It is further desirable that the gases act upon substantially the entire length of the arc path rather than merely upon one point of the path length.

Pole type arc-enclosing devices

The characteristic feature of pole type arc-enclosing devices is the provision of one common enclosure for all of the breaks in a pole unit. Inasmuch as the enclosure subdivides the body of oil within the breaker tank into only two parts, one within and one outside of the enclosure, this kind of breaker may be considered to be intermediate between the plain break breaker and a true arc-enclosing device breaker. The use of pole type arc-enclosing devices is generally limited to the lower interrupting capacities at 15 kv and below.

The expulsion port breaker shown in Figure 5 is a typical pole type arc-enclosing device breaker. A closed interrupting chamber is provided with two orifices situated immediately adjacent the two arc bubbles formed at the two points of break. These arc bubbles extend into and through the orifices provided in the interrupting chamber for egress of gaseous products of arcing. The gases under pressure which break from the arc bubbles through the body of oil to its surface result in a rapid violently turbulent flow within the bubble and the surrounding oil tending to deionize the arc path. The shrinking of the arc bubble due to venting is accompanied by an inrush of oil to the arc gap which is thus being filled by a dielectric as soon as arc extinction is achieved.

Filling of the arc gap immediately after arc extinction by a liquid insulating barrier is a characteristic feature of all oil circuit breakers. The arc path through the arc bubble is generally not cut by an inrushing oil barrier until some appreciable fraction of the half cycle following final arc extinction. Since oil accomplishes its function as a liquid insulator only following final arc extinction, the interrupting function of an oil breaker is not predicated upon the insulating property of liquid oil.

Stud type arc-enclosing devices

The classic design of the tank type oil breaker shown in Figure 6 comprises a pair of terminal bushings arranged in diverging relation on and supported by the top of the breaker tank. The upper diverging, and hence widely spaced, ends of the bushings project outside of the breaker tank and form terminals for connecting the breaker into an electric circuit. Current is carried from the upper diverging to the lower converging, and hence narrowly spaced, ends of the bushings by means of studs coaxially arranged within the bushings. Each of these bushing studs supports at its lower end a stationary breaker contact adapted to cooperate with a pair of movable breaker contacts. These movable breaker contacts are secured to a cross-bar which can be raised and lowered by means of an operating rod. Each of the bushing studs carries at its lower end, in addition to a stationary contact, a separate arc-enclosing device which surrounds each stationary contact. Hence the term, stud arc-enclosing device. When applying the more concise term, arc-enclosing device, it is generally intended to refer to a stud type arc-enclosing device. Stud type arc-enclosing devices are the only ones nowadays applied in higher voltage type breakers.

The earliest stud-type arc-enclosing device from which most of the more recent arc-enclosing devices are derived is the plain explosion pot shown in Figure 7. An explosion pot consists mainly of a strong shell of insulating material. The arc is drawn between a fixed contact arranged within the shell adjacent to one of its ends and a movable rod or bayonet type contact. The latter enters into and may be withdrawn from the shell through a narrow throat arranged at the end of the shell remote from the fixed contact.

When the pair of contacts part within the device, the gas generated by the arc produces a very high pressure in the space confined by the shell. That pressure tends to increase the speed of contact separation. The effect of the pressure in the shell combined with the effects produced by streams of vapor flowing turbulently from the arc-near bubble walls into the arc may cause arc extinction while the movable contact is still moving within the shell. Usually, however, interruption is accomplished by the axial arc-enveloping high velocity blast which is released when the moving contact is withdrawn from the orifice at the bottom of the pot. The effect of the sudden release of pressure is much like that of a minor explosion; hence the name "explosion pot."

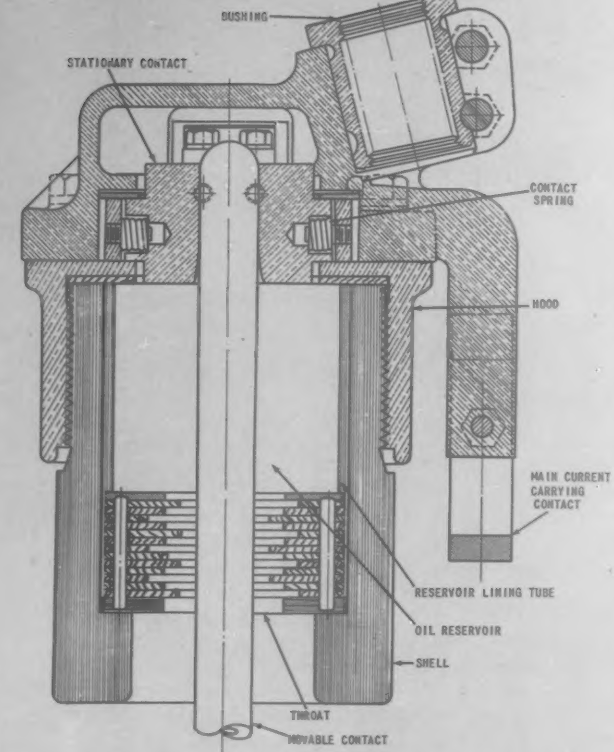
Modern low arc energy arc-enclosing devices are referred to by terms which either allude to their mode of operation or are trade designations pointing to their makers or both. Such terms are, for instance, explosion pot or oil blast pot, or "Deion Grid," or "Ruptor" interrupting device. Each device is made in various proportions and differing arrangements to adapt it to application at various voltages and interrupting capacities and for breakers of different speeds.

"Ruptor" interrupting devices

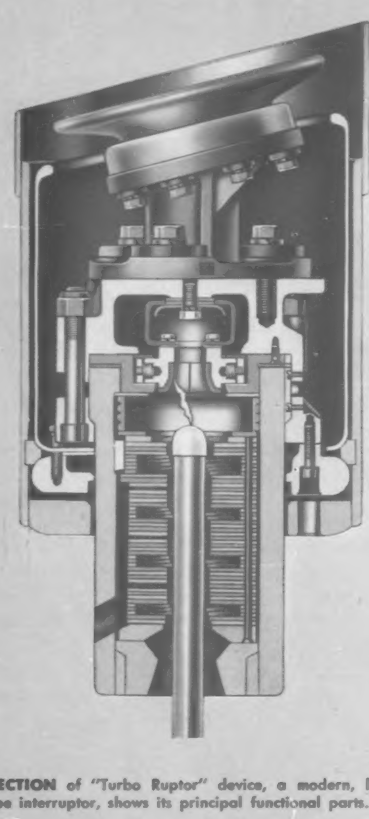
The design shown in Figure 8 is the forerunner of several generations of "Ruptor" interrupting devices. Structurally it differs essentially from the plain explosion pot in that it is provided with a relatively long throat member defining a passage of serpentine configuration. During the interrupting process the serpentine passage permits some controlled leakage by the bayonet contact while the latter is within the passage. As the bayonet contact is further withdrawn and the arc extended into the serpentine passage, pressure generated at the upper portion of the device causes a mixture of relatively unionized gas and oil to be turbulently impelled through the serpentine passage into the arc path.

Figure 9 is a vertical cross-section through a more recent version of the "Ruptor" interrupting device. The device shown in Figure 9 consists essentially of two main sections, the upper section which includes a support bracket and a tulip-type stationary arcing contact, and the lower or shell section comprising the pressure-generating chamber immediately below the stationary arcing contact and beneath it the throat assembly. The configuration of the throat differs from that of the earlier "Ruptor" shown in Figure 8 in that it provides a helically grooved contact passage which is made up by a stack of arc-resisting fiber laminations. The helical passage is designed to establish a helical path for gas and oil around the movable contact. During the interrupting process the lower section of the arc path is progressively extended into the throat and subjected to an intense deionizing action of fluid which is turbulently impelled into the arc path from the helical grooves by which it is laterally surrounded.

When the requirement for five- and three-cycle interrupting time breakers at higher voltages and interrupting capacities became apparent, the possibilities of the further development



LATER "RUPTOR" units had helical throats for gas and oil passage around the movable contact. Device interrupts in eight cycles. **(FIGURE 9)**



CROSS SECTION of "Turbo Ruptor" device, a modern, low arc energy suicide type interruptor, shows its principal functional parts. **(FIGURE 10)**

of the "Ruptor" principle and of the basic "Ruptor" structure were critically analyzed. Previous "Ruptor" designs had been simple and sturdy in construction and easily adjusted and serviced when required. The bayonet and tulip type contacts appeared to be preferable to butt-type contacts. The only possibility of retention of the features of structural simplicity and durability inherent in the eight-cycle interrupting time "Ruptor" device was further enhancement of the pressure-impelled deionizing action both as to rate of development and as to effectiveness upon the arc.

The "Turbo Ruptor" device design

Figure 10 shows a device embodying the realization of that possibility and known as "Turbo Ruptor" interrupting device because of its efficient dynamic arc-extinguishing action. The general appearance and the accessibility of parts are similar to earlier "Ruptor" versions except that improved electrostatic and insulating shielding have been added.

In order to meet the requirement for shorter interrupting times a shorter pressure generating chamber has been employed and higher contact speeds used so that the arc is elongated into the throat member at a much earlier point of time. The major change, however, is in the throat design.

A "Turbo Ruptor" throat comprises a stack of discs of oil absorbent insulating material of which each has punched-out portions. These punched-out portions define a cylindrical axial passage for the movable contact and a number of relatively steep-pitched coaxial helical oil passages which surround and communicate with the axial contact passage. The punched-out portions of the insulating stack also define a number of longitudinal venting passages arranged parallel to the axial contact passage, and several radial venting passages interconnecting spaced points of the axial contact passage with the longitudinal venting passages. The cross-sectional area of the helical oil passages is largest at the end of the stack adjacent the fixed contact and smaller at the end of the stack remote from the fixed contact.

Arc generated pressure impels a flow of oil through the helical oil passages. As the withdrawal of the movable contact through the axial contact passage progresses, the arc is progressively drawn into the portion of the axial contact passage cleared by the movable contact. Progressive withdrawal of the movable contact from the axial contact passage permits oil impelled by gas pressure to flow out of the helical oil passages in helical jets directed concentrically into the portions of the axial contact passage now occupied by the arc. Thus the multitude of helical oil passages provide an effective multiple front of attack by oil upon the arc, the arc being under concentric attack from all angles and at all levels. The arc reacts by decomposing the fluid impelled into it and by lowering the dielectric strength of the fluid. The fluid reacts in turn by producing blast conditions fatal to the arc. Fluid whose dielectric strength is impaired by arc action should be rapidly removed from the arc path so that fresh reserves of arc extinguishing fluid may be hurled at the arc path. This problem is solved in this design by the venting of electrically impaired arc-extinguishing fluid from the axial contact passage through the radial passages provided at spaced points for that purpose. Figures 11, 12 and 13 show the external appearance of "Turbo Ruptor" equipped breaker structures.

The "Ruptor" and other similar devices, comprising as their essential elements a pressure generating chamber arranged immediately adjacent the stationary arcing contact and a relatively

long and effective throat structure arranged beneath the pressure generating chamber, excel, within a wide range of interrupting capacity and interrupting time ratings, in both simplicity and sturdiness.

Design considerations and possibilities

The plain explosion pot operates in a generally satisfactory manner, as long as the current under interruption is neither too small nor too large, except that its arc energy is rather high. If the current under interruption is very small the arcing times tend to become excessive, and if the current under interruption is very large the high rate of generation of gaseous products resulting in excessive gas pressures tends to cause bursting of the pot. These limitations of the plain explosion pot are responsible for the development of more effective adaptations of the explosion pot principle of which some were here presented.

The high gas pressures occurring when the current under interruption is large compel provision of suitable venting means for pressure control and relief. Explosion pots may be top vented or side vented, in addition to being bottom vented. Each possible arrangement has its particular potentialities and limitations. The "Turbo Ruptor" device shown in Figure 10 is both side and bottom vented.

One of the alternatives for overcoming the limitations of the plain explosion pot, and other early similar devices, as to interrupting capacity and interrupting time, is the use of multibreaks in series in combination with resistor means for distributing the recovery voltage evenly between the breaks. It is a meritorious feature of multibreaks to permit rapid insertion of arc resistance into the circuit. The weak point of multibreaks consists in that they involve relatively complicated contact structures and operating mechanisms.

Another alternative for increasing interrupting capacity and decreasing interrupting time is the use of resistors which shunt the arc gap to limit the rate of rise of the recovery voltage. The shunt resistor principle was applied to oil breakers early in the century but was then discarded because designers could not produce a practical embodiment of the principle. As a consequence of extensive use of shunt resistors in air blast breakers, reliable resistor arrangements were developed and they are now a ready tool in oil breaker design.

A design principle permitting increase of interrupting capacity and decrease of interrupting time which has been more widely applied in Europe than in this country is the differential piston type arc-enclosing device. Such a device relies on a piston pump for producing an arc-extinguishing blast. The piston of the piston pump has a relatively large surface being acted upon by the arc gases and a relatively small surface acting upon the body of oil for producing an oil jet directed against the arc gap.

Suicide and impulse breakers

Interrupting devices in which energy supplied by the circuit under interruption produces an arc extinguishing action are often referred to as suicide type devices. In arc-enclosing devices of the explosion pot type the arc produces the gas pressure responsible for the formation of an arc extinguishing blast. Therefore, arc-enclosing devices of the explosion pot type are suicide type devices. The higher the current under interruption, the higher the gas pressure generated within the device and the deadlier the self-inflicted deionization of the arc path. Since the arc extinguishing action increases as the current under interruption increases, both arc length and arc duration tend to decrease with increasing current.

As already pointed out, any variant of the explosion pot is subject to a tendency toward long arcing times if the current under interruption is very small. This tendency may be minimized by appropriate design features. In any suicide type oil breaker the accumulation of sufficient arc energy and its conversion into flow energy involves a time element, however small, tending to delay the final interruption of the circuit.

Oil impulse breakers are intended to overcome these limitations of suicide type oil breakers. In oil impulse breakers an arc extinguishing oil jet aimed at the gap formed between the separating contacts is produced by a piston pump which is externally energized, either by spring means or compressed air. While external energization of the piston pumps tends to free oil impulse breakers of the limitations of suicide type oil breakers, this advantage is achieved at the cost of mechanical complications involving more labor and material.

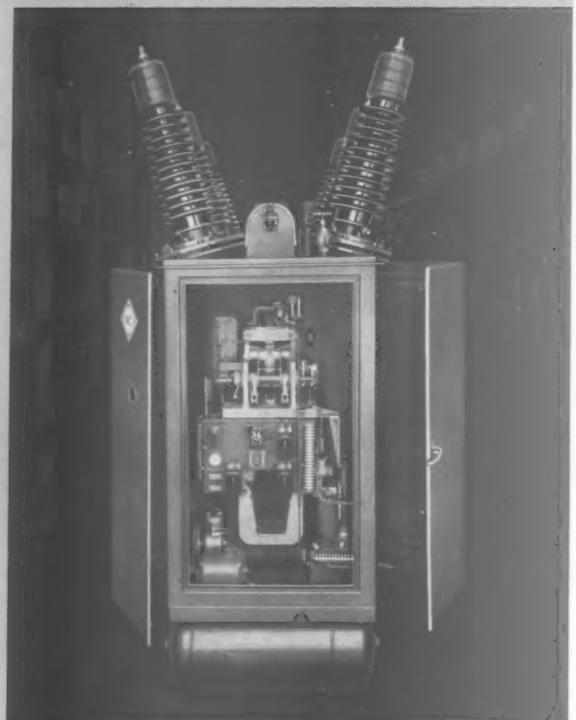
The oil impulse breaker has many features in common with the air blast breaker. This is mainly due to the fact that both rely on the common principle of pre-storing blast energy in ready-to-act form. Because of this fact, both kinds of breakers are capable of producing substantially constant blast pressures irrespective of the current under interruption and their arcing times do not increase with decreasing current strength.

Other common features of the oil impulse breaker and of the air blast breaker are the short length of their strokes from the fully closed to the fully open position and the relatively light weight of the movable contact structures. Because of these features, both types of breakers lend themselves particularly well to ultra high-speed operation.

Since it is possible to economically design suicide type breakers capable of clearing short-circuits in interrupting times as short as five or three cycles, the suicide principle is much more widely applied than the oil impulse principle. This is due to the fact that suicide type breakers are now generally provided with various refinements as required to overcome the original limitations of the suicide principle and to otherwise improve breaker performance. One such refinement in current use consists in forming two serially related arcs in the arc-enclosing device of which one arc generates pressure to produce an arc extinguishing fluid blast across the other arc. The former arc is generally referred to as pressure-generating arc and the latter arc as interrupting arc. The elongation of the pressure-generating arc may be limited to limit pressure at high current shots. The pressure-generating arc may be drawn between an upper contact and an intermediate contact and the interrupting arc between the intermediate contact and a lower contact. Such an arrangement makes it possible to establish both arcs in very rapid succession, or even simultaneously, thus tending to reduce the time required to initiate effective interrupting action. Some suicide type oil breakers are provided with a small piston pump for establishing an auxiliary oil flow in addition to the oil flow established by the pressure-generating arc. While provision of such a piston pump constitutes a complicating design factor, it achieves the dual function of establishing an auxiliary oil flow for low current arc extinction and a scavenging oil flow for disposing of the residue of the arc in case of high current arc extinction.

Tank type and low oil content breakers

It is possible to distinguish between these two types of oil



OPEN CONTROL CABINET shows the operating mechanism of an oil circuit breaker equipped with a "Turbo Ruptor" device. U-shaped support is for hydraulic jack which is used only for operation during maintenance checkup. **(FIGURE 11)**

BIRD'S EYE VIEW of oil circuit breakers under construction shows the V-arrangement of bushings on each breaker tank. Lower end of each bushing supports a "Turbo Ruptor" device. **(FIGURE 12)**

breakers, depending upon their oil content and the way in which insulation of live parts is achieved.

As previously mentioned, so-called tank type breakers have their stationary contacts and arc-enclosing devices arranged within a large oil-filled steel tank. The tank is at ground potential and oil insulates all live parts from ground. This type of breaker requires, therefore, relatively large tanks and volumes of oil, increasing in proportion to the voltage rating of the particular piece of apparatus in question.

In the low oil content breakers, often also referred to as oil poor breakers, oil is used for arc extinction by blast action, but its use is mainly limited to this function and little use is made of its dielectric strength for insulating live parts from ground. In low oil content breakers, the oil-filled arc-enclosing chamber is arranged within a hollow porcelain insulator which insulates the live parts of the breaker from ground, thus making it possible to greatly reduce the oil volume compared to the volume of oil needed in tank type oil breakers. Small oil volume breakers are generally of the impulse type.

Oil breaker trends

The trend of the recent past and the current trend indicate a tendency toward higher interrupting capacities and shorter interrupting and arcing times and still lower arc energy. The present maximum standard rating is 5,000,000 kva. Breakers having even higher interrupting capacity ratings have been — or are in the process of being — developed. In recent years, available rated interrupting times were progressively reduced from twelve to eight to five and finally to three cycles. As regards the reduction of arcing time, designs requiring many cycles of arcing were superseded by designs requiring but a few half cycles or even only half a cycle of arcing. The trend is toward oil breakers with consistently short arcing times over the entire interrupting range.

The trend toward higher interrupting capacities has two aspects: higher current interrupting capacities at existing transmission voltages and higher voltage ratings for contemplated new transmission systems operating at higher voltages.

There is a trend toward building transmission lines at minimum cost by reducing insulation levels. Reduced insulation levels make it increasingly important to minimize overvoltages due to switching operations, among which those caused by restriking when interrupting capacitive charging currents, e. g. those of long transmission lines, are most dangerous. More attention than heretofore is, therefore, being given to the characteristics of breakers when interrupting capacitive circuits as well as to their ability to interrupt both large and small currents.

During the earlier period of power system development it was the primary object of system and other engineers interested in system performance to provide sufficient power at a high level of reliability. This goal is now achieved, in substance, and cost consciousness has become a dominating factor. The trend is now unquestionably toward reduction of capital investment and operating cost. There is not one single breaker design which is not directly or indirectly affected by the current trend toward greater economy. The recently increased emphasis on simplified breaker maintenance and increased ease of handling is but a necessary outgrowth of increased cost consciousness.

Merits of the oil breaker

When considering the merits and potentialities inherent in a given design principle, it is always well to revert to funda-

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mentals. A-c circuit interruption is basically a process of energy dissipation. It is also an insulation problem. As previously pointed out, the process of oil disintegration is an excellent energy-absorbing mechanism. Furthermore, oil is an excellent dielectric and is fully utilized as such in tank type breakers. These are the reasons, in a nutshell, which account basically for the success of the oil breaker in general, and in particular that of the tank type.

Air blast as well as oil breakers can be built for any required interrupting duty. The choice between different breaker types is a matter of economics, a matter of cost of labor and material, rather than a matter of technical limitations. Since prime costs may be different in different countries, it is well possible that a breaker type may appear to be preferable in one country and another breaker type in another country.

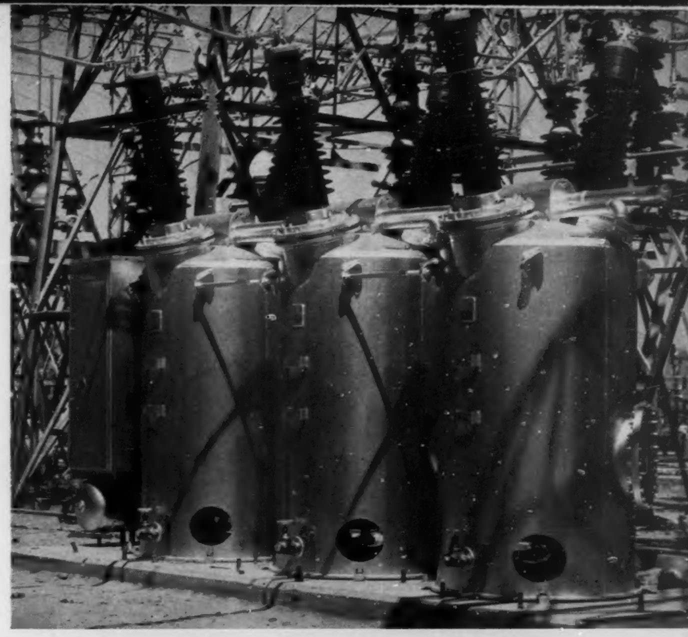
A point to which reference is frequently made is that of fire hazard. Air blast breakers are oilless, small oil content breakers contain but small amounts of oil, while tank type oil breakers contain relatively large amounts of oil. Normally, this makes little difference so far as fire hazard is concerned, since any modern oil breaker may be considered to be explosion-proof unless exposed to enemy action.

Breaker economics is a matter inseparably tied together with the economics of auxiliary equipment, such as current transformers and potential measuring devices. The bushings of tank type oil breakers lend themselves to the use of ring-type-bushing current transformers which are less expensive than the type required for use with air blast or small oil content breakers. Similarly, the bushings of tank type oil breakers lend themselves at little or no extra cost as capacitance voltage dividers for voltage measurements, while potential transformers required for use with air blast or small oil content breakers are rather expensive pieces of equipment. The economy inherent in ring-type-bushing current transformers and bushing capacitance voltage dividers is due to the fact that in such arrangements the requisite insulation is provided by the bushing itself, whereas in other arrangements the requisite insulation must be provided by additional insulating means. Since each breaker needs several current transformers, and often voltage measurement means, the tank type oil breaker has quite an edge over other type breakers so far as the economics of auxiliary equipment are concerned.

Test data useful in design

To test an electrical apparatus is to determine its performance characteristics while functioning under controlled conditions. Of course, any electrical apparatus, including any type of breaker, oil or otherwise, must be tested.

Early in the century manufacturers of power circuit breakers had almost no means for ascertaining how their breakers would perform under actual operating conditions. Users of circuit breakers were sometimes supplied with apparatus having defects that did not show up for years in service. As time went on, manufacturers of circuit breakers and utility companies got together for cooperative field testing. Initially, field tests were sporadic and were carried out under most unfavorable conditions. Yet the design data resulting from such tests often proved to be of such value as to warrant the hazards of deliberate short-circuits on power systems with their risks as to rotating machinery, transformers, etc. As time went on, cooperative testing became well organized. Some cooperative field tests are landmarks largely determining future design trends. A new era in the development of breakers was initiated with the advent of industrial high-power testing



PNEUMATICALLY OPERATED, 115-kv, three-pole oil circuit breakers with the "Turbo Ruptor" interrupting unit. **(FIGURE 13)**

laboratories. The large test generators in such laboratories make it possible to produce safely at any time a large variety of predetermined short-circuit conditions. Evaluation of such tests is greatly facilitated by permanently installed, ever-ready measuring and recording apparatus.

While power concentration and the interrupting capacity required of circuit breakers increases continually, there are economic limits to the size of test generators for laboratory use. The requirements in the field as to interrupting capacity quite often exceed the largest power which any high power laboratory is capable to provide. This has led to "synthetic" methods of laboratory testing involving particular circuit connections which yield test data permitting extrapolation to higher powers than those under which the tests are actually made. Another artifice which renders it possible to predict the performance of breakers for extremely high power consists in making up a given breaker of a number of interrupting units, testing each unit separately and extrapolating the test data so obtained to the interrupting performance of a composite multi-unit structure. Notwithstanding the importance of "synthetic" testing, final and complete proof must always come from field tests and the service records.

Quantitative investigation speeds progress

The great progress achieved in mechanical engineering during the 19th and 20th centuries is mainly due to the application of methods of quantitative analysis based on the principles of Newton's system of mechanics. The great progress achieved in the field of rotating machinery and transformers late in the 19th and during the 20th century is likewise due to the application of methods of quantitative analysis resulting in predictability during the design stage of future performance. The fact that the theory of electromagnetism was known in its essential parts at the very outset of the industrial development of rotating machinery and transformers and that it grew simultaneously with such development made it possible to attain today's high level of achievements within a relatively short period of time.

In the 19th and at the beginning of the 20th century knowledge remained rather superficial in fields lacking such reliable

mathematical tools as Newton's system of mechanics or the theory of electromagnetism. Consider, for instance, biology or medicine. Matters of biology or medicine were generally much too complex for a comprehensive quantitative approach. Hence the majority of investigations had to be confined to qualitative aspects and random trial and error experimentation.

Because of a lack of quantitative knowledge of fundamentals of circuit interruption, the quantitative exploration of breakers in general, and more particularly that of the oil breaker, lagged behind that of rotating machinery and transformers. Fortunately quantitative exploration of breakers was never as handicapped by the complexity of the matter as were, for instance, biology or medicine. Breaker operating mechanisms always could be explored by application of Newton's system of mechanics; many mechanical and electrical stress problems could be solved by application of the laws of electromagnetism and electrostatics. But the limits for quantitative analysis were relatively narrow. Not so long ago our knowledge of the mechanism of the arc discharge was meager. We knew little or nothing about the interaction of the arc with highly complex organic substances, such as oil.

The present situation is very different. Tremendous progress has been achieved during the last fifteen or twenty years in breaker theory and design. Modern physics of the discontinuous subdivisions of our apparently continuous material world—the molecule, the atom and the subatomic particles—have opened new avenues for quantitative investigation of circuit interruption. While the maze of interrelated facts upon which the performance of circuit breakers depends is too complex to permit exact pre-calculations of the kind possible in the creation of rotating machinery and transformers, we may nevertheless truly say that we have found our bearings as to a quantitative understanding of the interrupting process.

The future of our electrical age, including our everyday lives, depends to a considerable extent on the way in which our ever more exacting fundamental power transmission problems are going to be solved. Top-ranking among these problems are those related to rapidly opening a faulted circuit to rapidly clear the fault before it can do any serious harm and to reclose the circuit after the fault has been cleared so rapidly that continuity of service is not impaired.

We expect that power system protection will be able to solve these problems in all the modifications in which they may arise. Our confidence is based on the fact that the progress in circuit breaker theory and design achieved since guesswork yielded to quantitative methods has hardly ever been surpassed anywhere in electrical power engineering during any period in all its history.

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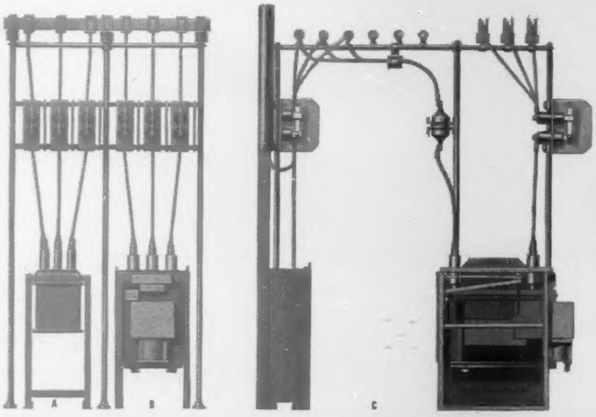

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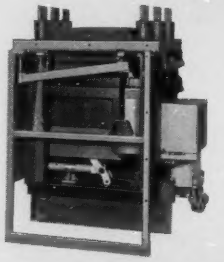

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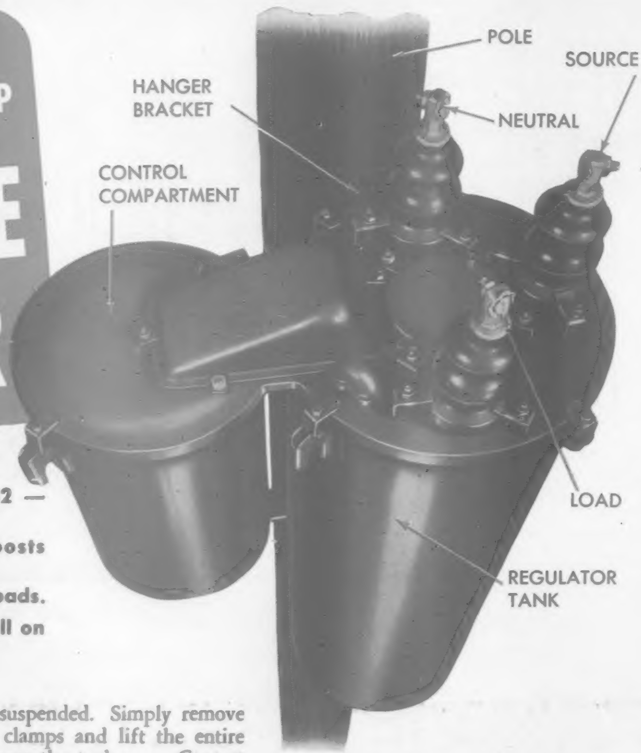

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Easy maintenance — easy mounting — simple control are provided. First, it is cover-suspended. Simply remove four cover clamps and lift the entire regulator from the tank. . . . Contact life is long. . . . Quick-break mechanism eliminates arcing and pitting. In addition, because of small 5/8% steps, contacts interrupt smaller kva — last longer. Unit is mounted on pole as easily as distribution transformer. . . . Control requires just two simple knob adjustments to set.

Ask an Allis-Chalmers field engineer to determine the best means of improving voltage conditions on your rural system using voltage regulators. Contact a nearby A-C Sales Office or send in the coupon.

A-2779

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Allis-Chalmers, 848-A S. 70th St.
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☐ Send me descriptive bulletin plus "When and Where to Apply Rural Voltage Regulators"

☐ Have engineer call.

Name..........

Title..........

Company..........

Street..........

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